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U.S. Coast Guard/U.S. Maritime Administration
Cooperative Research on Marine Engine Exhaust Emissions

EXPERIMENTAL DESIGN ON MARINE EXHAUST EMISSIONS

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16. Abstract

Important variables in the operation of internal combustion engines were identified, and statistically-designed experiments were developed to evaluate the multivariate interactions for both diesel and spark ignition engines. For the lab engines: the diesel design included use of dual fuels (natural gas in diesel fuel); the spark ignition engine included the use of propane as well as gasoline. Experiments conducted on the diesel engine showed reduced exhaust emissions at high levels of natural gas (80%), but only at reduced compression ratios.

Still another design was developed for shipboard testing using portable emissions equipment. This design was applied to three 82' CG Cutters (WPBs) and their emissions measured according to ISO 8178 protocol. The results showed no significant difference based on depth between 30 and 120 feet. Carbon monoxide was reduced with increased engine load (e.g., higher speed, or towing), whereas the NOx output was fairly constant for a given shaft rpm. The NOx value levels off at about 10 g/kW-hr or 25 kg/tonne fuel; CO at about 2 g/kW-hr or 6 kg/tonne of fuel.

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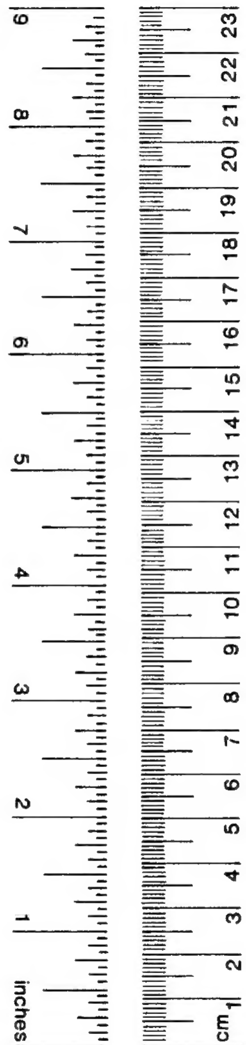
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

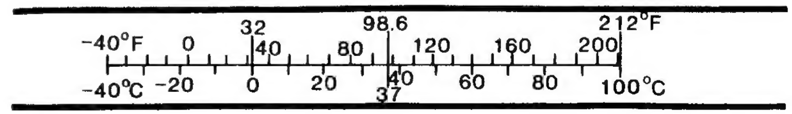


TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

The U.S. Coast Guard is beginning a detailed examination of emission factors for Coast Guard cutters. This examination is part of a larger U.S. Coast Guard and U.S. Maritime Administration cooperative research effort concerning marine engine exhaust emission assessment and control. The information will be used for guidance in assuring that the Coast Guard can meet the standards promulgated under the Clean Air Act, as amended in 1990 (CAAA90). Coast Guard cutters are often stationed in the harbors of major U.S. cities which have trouble meeting the requirements of CAAA90. As a result, restrictions are placed on the exhaust emissions of ships and boats as well as other transportation forms. The Coast Guard is expected to meet these requirements along with private ships and boats.

The current study involves a survey of existing conditions and determination of the most prominent factors to be considered in improving propulsion engine emission performance. This study involves both laboratory research using Cooperative Fuel Research (CFR) engines and shipboard testing using "Point" class 82 ft WPBs. A statistically sound experimental design was required to ensure data was collected on a sound basis. This was particularly important because the data must ultimately be compared to international test results. Since the Coast Guard is the International Maritime Organization (IMO) representative for the United States, it is imperative that the results be above question.

1.2 Scope

This study consisted of two primary phases: shipboard tests and CFR engine laboratory tests. MAR, Inc., recommended independent and dependent variables for consideration in each phase (Appendix A). A test protocol was prepared by MAR for the shipboard tests which was used by the Coast Guard Research and Development Center (R&D Center) as guidance during tests on three 82 ft WPBs (Appendix B). MAR analyzed the test results and provided these to the R&D Center. MAR also prepared experimental designs for use with a diesel CFR engine (Appendix C) and a spark ignited CFR engine (Appendix D) located at the Coast Guard Academy in New London, CT. The experimental design was followed by the R&D Center during tests on the diesel CFR engine. No tests were run on the spark ignited engine. MAR analyzed the experiment's results and determined best fit equations for each dependent variable based on the levels of the independent variables. Both the shipboard tests and CFR engine tests are discussed in this report along with conclusions drawn from this testing.

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2 IDENTIFICATION OF VARIABLES

The first task in this project was identification of the independent and dependent variables of interest. Appendix A contains the paper on variable identification prepared by MAR, Inc., for this task.

For the shipboard tests, it was desirable to follow the procedures in International Standards Organization (ISO) 8178 series as closely as possible so that the results can be compared to other international test results. For this reason, a procedure similar to that for the marine test cycle in ISO 8178, Part 4, was proposed. Under this test cycle, data is taken at 5 shaft rpms that have been selected to represent frequent operating points. A weighted average of the data is then taken to represent the single number emissions of the cutter. This is equivalent to varying RPM and torque (fixed by the propeller) as independent variables.

The laboratory tests on the CFR engines provide for more flexibility in choosing independent variables. MAR recommended the following independent variables be used based on the limitations of the test engines.

a. Engine RPM
b. Engine Torque
c. Compression Ratio
d. Injection Timing (Spark Timing)
e. Inlet Air Restriction
f. Fuel Type (Diesel/Natural Gas) (Gasoline/Propane)
g. Fuel Additives (Optional)
h. Exhaust Back Pressure (Optional)

For both the laboratory tests and the shipboard tests, the dependent variables were the same. These consisted of measurements of the concentration of various emitted gases. Data on ambient conditions and engine operating parameters were taken as necessary to permit data analysis.

3 TEST PROTOCOL FOR SHIPBOARD TESTS

A test protocol, Appendix B, was prepared for use during the shipboard tests. This protocol describes several tests to exercise the engines over as wide a range of operating conditions as possible under the limitations imposed by the torque requirements of the propeller. The protocol was written for use with any cutter class but was used in this study only on the 82 ft WPB class. The protocol describes the data that must be collected and the operating conditions that have to be maintained.

The primary tests in the protocol were free running tests at various shaft RPMs. These tests were designed to collect data at 5 operating points that could be used to provide a single weighted average of pollutants for the cutter. The free running tests evaluate the cutter in its usual operating condition of solo steaming.

Ahead and astern acceleration tests were recommended to measure the transient, high loading conditions on the engine that such accelerations impose. These require continuous recording of test parameters over several minutes time. Deceleration tests were also recommended to measure the unloaded deceleration emissions of the engines. Again, continuous data recording is required.

The final tests proposed consist of heavier than normal loading conditions such as those encountered during towing operations or extremely shallow water operations. The cutter's speed is reduced in these conditions and the propeller torque is higher than in the free running condition for a given shaft RPM. This higher load should change the engine emissions.

For most ships, it is extremely difficult to measure the intake air flow rate for each engine. This is a key parameter used to determine the exhaust flow rate and the emission rates. A technique has been developed to avoid this difficulty by balancing the amount of carbon from compounds in the intake air, fuel, and exhaust gas to determine the required flow. This carbon balance approach was proposed in the test protocol.

4 SHIP TEST RESULTS

4.1 Data Analysis

A number of different types of comparison test runs were made to determine the effect of engine loading on emissions. However, the same data was taken for all test runs. The method used to analyze these data is described in this section with the results of the analysis discussed in sections that follow. The procedures and nomenclature in ISO standard DP 8178-1, RIC Engines - Exhaust Emission Measurement, were followed in making calculations.

In some cases part of the data was missed due to instrumentation failures. However, sufficient data were collected to permit the missing data to be estimated based on a regression analysis on the data that was collected. A regression curve was fitted to the available data and this curve was used to estimate the value of missing parameters.

Because the intake air flow is generally not measured, the test protocol for shipboard testing envisioned using a carbon balance approach to determining the exhaust mass flow. The R&D Center was able to purchase an air flow measuring device adaptable to the caterpillar engines on the 82 ft WPBs. With air flow available, the data analysis was greatly simplified.

The following data were collected:

a. Barometric Pressure (Inches of mercury) {29.92" Hg = 101.33 kPa}
b. Relative Humidity near intake (percent)
c. Temperature associated with Relative Humidity (°F)
d. Intake Air Temperature (°F)
e. Shaft RPM
f. Engine RPM
g. Shaft Horsepower (Horsepower) {1 HP = 0.746 kw}
h. Fuel Flow Rate (U.S. gallons/hour) {1 gal = 0.0037854 m^3}
i. Intake Air Flow Rate (cubic feet/minute) {1 cu.ft. = 0.028313 m^3}
j. Stack Temperature (°F)
k. Oxygen volume (dry) in exhaust (percent)
l. CO volume (dry) in exhaust (ppm)
m. CO_2 volume (dry) in exhaust (percent)
n. Excess Air volume (dry) in exhaust (percent)
o. NO volume (dry) in exhaust (ppm)
P. NO_2 volume (dry) in exhaust (ppm)
q. NO_X volume (dry) in exhaust (ppm)

The following parameters were calculated based on the above data:

GFUEL - Fuel Mass Flow Rate (kg/hr)

GFUEL = 0.00379 x Fuel Flow Rate (gal/hr) x Fuel Density (kg/m^3)

Fuel Density = 833 kg/m^3 for the diesel fuel used.

GAIRD - Dry Air Mass Flow Rate (kg/hr)

GAIRD = 1.698 x Intake Air Flow Rate (ft^3/min) x Dry Air Density (kg/m^3)

Where the coefficient changes units of volume and time.

A Psychrometric chart for a pressure of 30.00" Hg was used to determine the air density at the measured relative humidity and temperature.

GH2O - Water Mass Flow Rate (kg/hr)

GH2O = 1.698 x Intake Air Flow Rate x Absolute Humidity x Dry Air Density

Where Intake Air Flow Rate is in ft^3/min,
Absolute Humidity is in (kg H_2O)/(kg Dry Air), and
Dry Air Density is in kg/m^3.

A Psychrometric chart for a pressure of 30.00" Hg was used to determine the absolute humidity and air density at the measured relative humidity and temperature.

GEXHW - Exhaust Mass Flow Rate (Wet) (kg/hr)

GEXHW = GFUEL + GAIRD + GH2O

FFH - Fuel Specific Factor representing the hydrogen to carbon ratio

FFH was taken from Table (9) in ISO/DP 8178-1 for diesel fuel based on the excess air measured in the exhaust. Factor has a range of 1.783 - 1.920. This factor is used to correct the dry concentrations of measured gases to wet concentrations.

KW - Dry to Wet correction factor

$$KW = \left(1 - FFH \times \frac{GFUEL}{GAIRD} \right) - KW2$$

$$\text{Where } KW2 = \frac{1.608 \times \text{Absolute Humidity (g/kg)}}{1000 + \text{Absolute Humidity (g/kg)}}$$

$$\text{Concentration(wet)} = KW \times \text{Concentration(dry)}$$

Gas Mass Flow Rate (grams/Hour)

Exhaust gas flow rates measured in ppm or percent are by volume. These need to be converted to a mass basis.

$$\text{Gas Mass Flow Rate} = u \times \text{Concentration(wet)} \times \text{GEXHW}$$

Where u is in grams of gas/kg of exhaust,
Concentration(wet) is in ppm or percent, and
GEXHW is in kg/hr

$$u = \frac{4.4615\times10^{-5}\ (\text{Mol/m}^3) \times \text{Molecular Weight (g/Mol)}}{\rho_{air}\ (\text{kg/m}^3)} \quad \text{for concentrations in ppm}$$

ρ_{air} = 1.293 kg/m^3 at 0 °C and 101.33 kPa pressure

Power (kw) = Shaft Horsepower x 0.746 (kw/HP)

Emissions (g/kw-hr) = Gas Mass Flow Rate (g/hr)/Power (kw)

Emissions (kg/tonne fuel) = Gas Mass Flow Rate (kg/hr)/GFUEL (metric tons/hr)

NO/NOx = Volume ratio (dry)

O_2 Weight Fraction = Wet O_2 (kg/hr)/GEXHW (kg/hr)

4.2 USCGC POINT FRANCIS

The USCGC POINT FRANCIS which operates out of New London, CT, was tested on the 13th and 16th of August 1993. Tests consisted of free running tests with and against the current, and a shallow water and deep water comparison. However, the shallow water runs were conducted in approximately 30 feet of water which creates very little extra loading for a boat of the 82 ft WPB's size. The deep water runs were made in approximately 120 feet of water. No acceleration/deceleration runs were conducted on the POINT FRANCIS or on the other two cutters tested because of problems with continuous data recording with the test instrumentation used.

Notes on Data Analysis

Missing and Erroneous Data

Several blocks of data were missing or clearly bad. These were:

Intake Airflow (Starboard) for tests 18 and 19
Intake Airflow (Port) for tests 19 to 46
NO_2 (Port) for tests 34 to 46

For each of these three cases independently, the existing data was plotted, fitted with a second order regression line, and the regression line was used to reconstruct the missing or bad data.

The fuel consumption values, provided as averages for each group of tests, were entered individually for each test in the group.

Shaft horsepower values were changed arbitrarily to 0 at Idle (declutched) and to 5.5 at Clutch RPM to avoid the wide variation in quantities measured at these two operating points.

Calculation of Fuel Mass Flow Rate

Fuel mass flow rate was calculated assuming a fuel density of 0.833 g/cm^3 .

The formula used to calculated fuel mass flow was:

GFUEL (kg/hr) = 3.153 x Flow (gal/hr)

Calculation of Air and Water Mass Flow Rates

A Psychrometric chart for 30.00" Hg was used in these calculations. Entering the chart with the measured 25% relative humidity and 45.55°C, the absolute humidity was found to be 0.0156 kg H_2O/kg dry air, or 1.53% by total weight, and the specific volume of the air was 0.923 m^3/kg dry air.

This equates to densities of 1.0834 kg dry air/m^3, 0.0169 kg H_2O/m^3, and a total density of 1.1003 kg wet air/m^3 at 45.55°C and 30.00" Hg pressure.

The actual barometric pressure was in the range 30.13 - 30.15" Hg. The inaccuracies in the air and water mass flow rates resulting from the difference in the specific volume of the air from 30.00" Hg to 30.13" Hg were deemed insignificant with respect to other experimental errors and with respect to the accuracy with which the Psychrometric chart could be read, and were thus ignored.

The Dry Air Mass Flow rate (GAIRD) was calculated as:

GAIRD (kg/hr) = 1.8407 x Airflow (ft^3/min)

The Water Mass Flow Rate (GH2O) was calculated as:

GH20 (kg/hr) = 0.0287 x Airflow (ft^3/min)

The total exhaust mass flow rate, which is equal to the total intake mass flow rate, was calculated as:

GEXHW (kg/hr) = GFUEL + GAIRD + GH2O

Determination of the Fuel-Specific Factor

The Fuel-Specific Factor (FFH) was interpolated manually from a plot of excess-air factor vs. FFH prepared from the three points given for diesel fuel in Table 9 of ISO 8178-1. The Excess Air Percentage reported in the data was assumed equal to the Excess-Air Factor.

Correction of Dry Emissions to Wet

The exhaust concentrations of O_2, CO, NO, and NO_2 were reported in ppm by volume (dry). These were converted to ppm by volume (wet) by the procedure outlined in Section 13.2 of ISO 8178-1. The conversion factor KW is calculated independently for each test run by Equation 13 of Section 13.2. The humidity factor KW2 was a constant, equal to 0.0247 for 15.6 g/kg absolute humidity.

Calculation of the Emission Mass Flow Rates

The wet volume fractions of pollutants were converted to mass fractions of the total (wet) exhaust mass flow by the procedure outlined in Section 13.4 of ISO 8178-1. Coefficients for use with NO and SO_2 were calculated using the formula for "u" in section 4.1.

Test Results

Only selected test results are shown here. Others of less importance have been provided separately to the Coast Guard. The following pages show plots of NO_X on the basis of g/kw-hr and kg/tonne of fuel. Similar plots are shown for CO. All plots are for free running operations on both engines in two water depths, 120 feet and 30 feet. A plot of the oxygen in the exhaust is also shown. Oxygen in the exhaust showed a similar response with increasing RPM for all three ship tests.

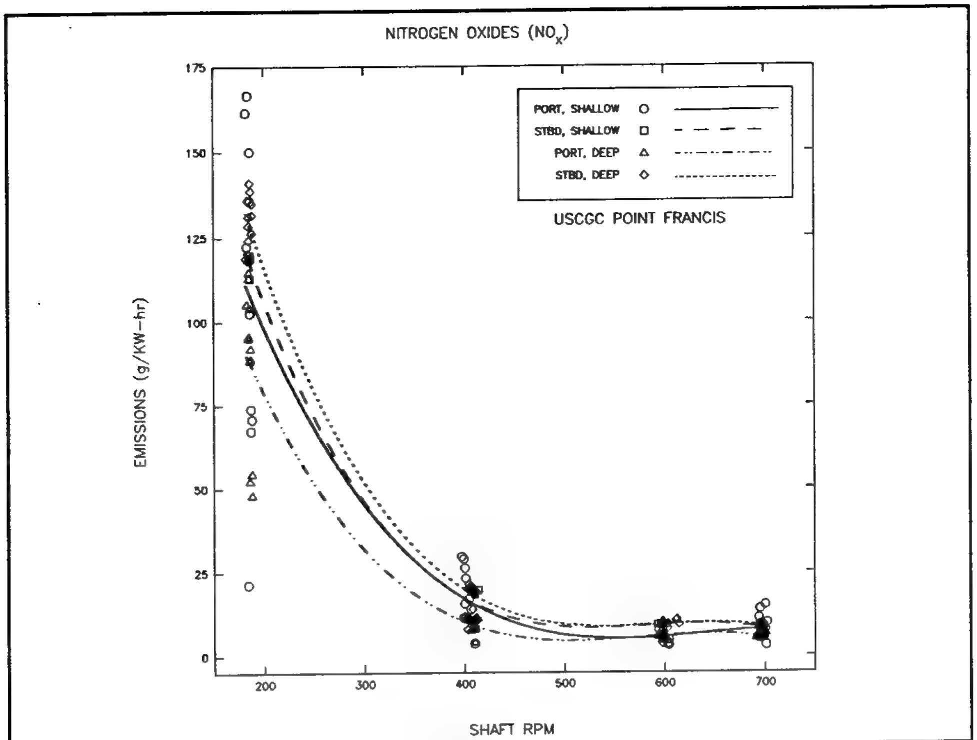


Figure 1 PT FRANCIS NO_X (g/kw-hr) versus Engine Speed

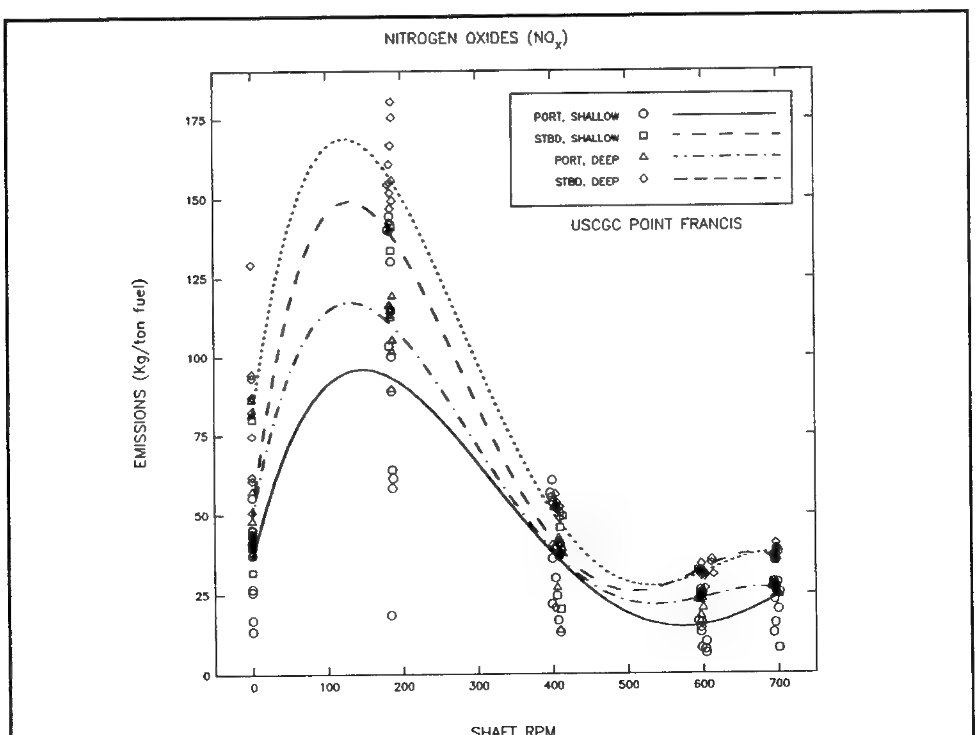


Figure 2 PT FRANCIS NO_X (kg/tonne fuel) versus Engine Speed

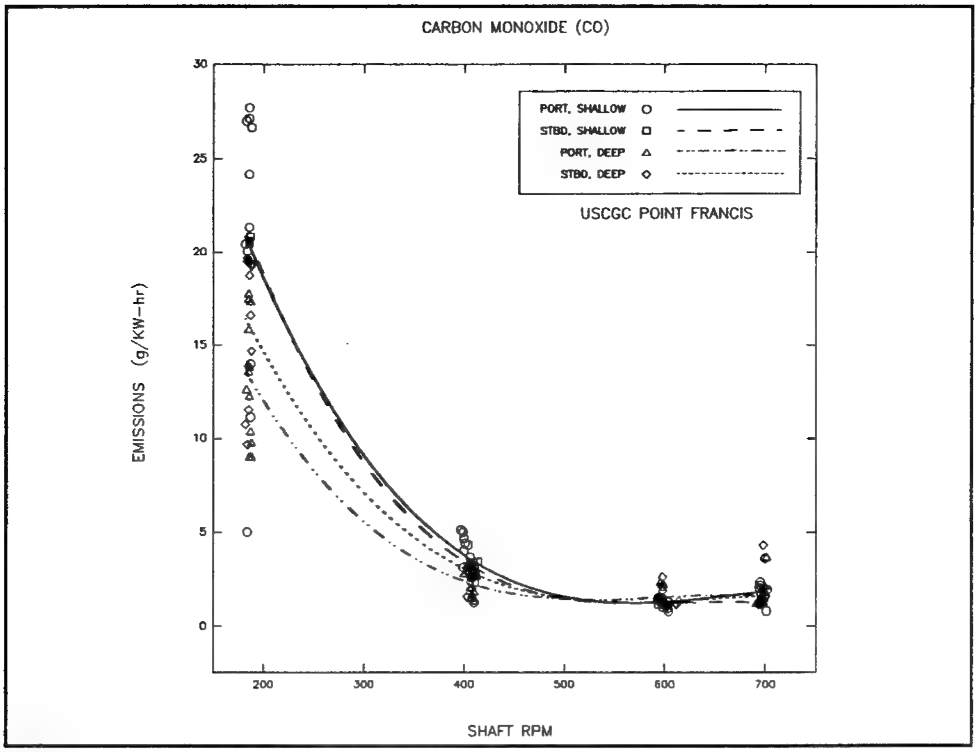


Figure 3 PT FRANCIS CO (g/kw-hr) versus Engine Speed

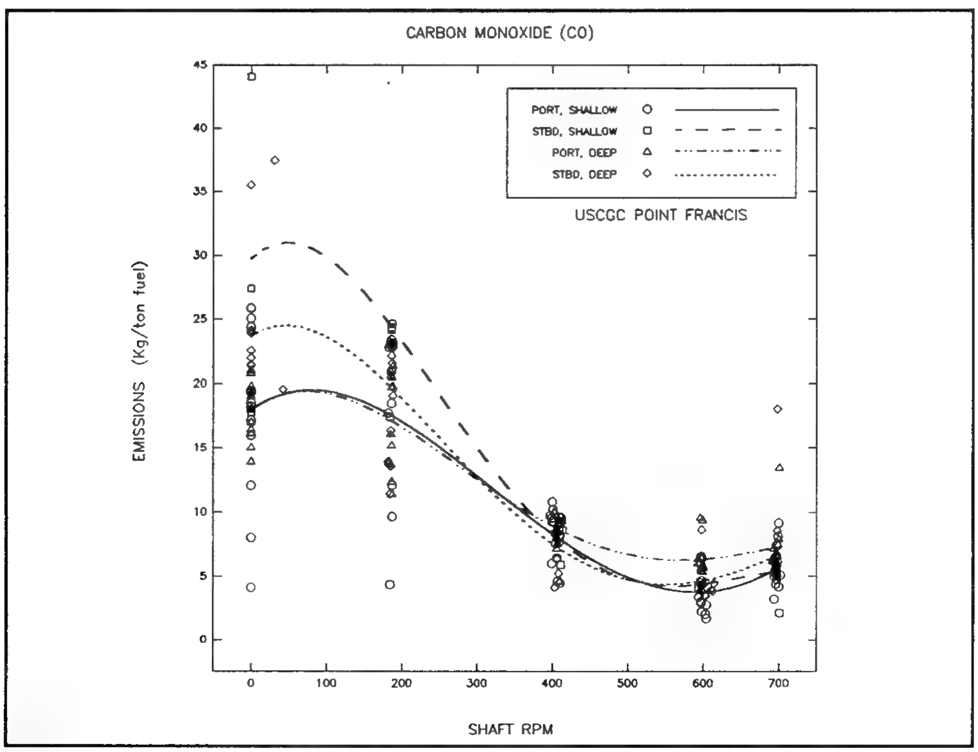


Figure 4 PT FRANCIS CO (kg/tonne fuel) versus Engine Speed

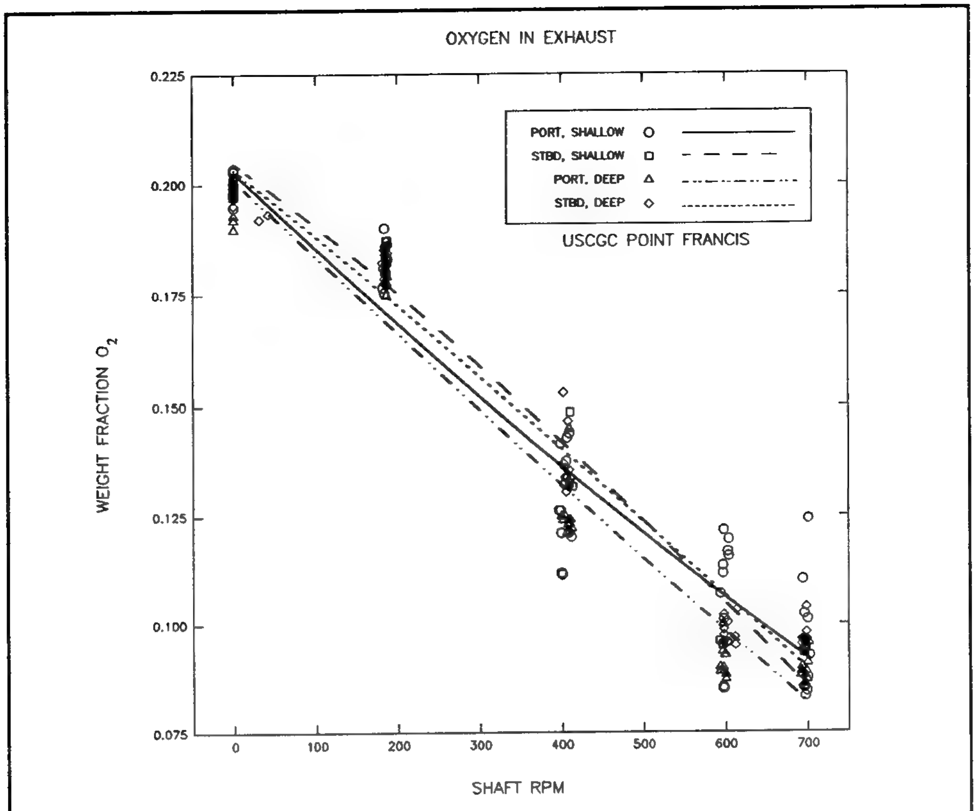


Figure 5 PT FRANCIS Oxygen in Exhaust versus Engine Speed

4.3 USCGC POINT BROWER

The USCGC POINT BROWER operates out of San Francisco, CA, and was tested on September 28 - 30, 1993. Tests were conducted in 20 foot and 30 foot depths. Also, towing tests were conducted with both engines and with the port engine alone. These tests showed the effects of engine loading on emissions.

Notes on Data Analysis

Missing and Erroneous Data

Several data fields were missing or clearly bad. These were corrected as follows:

Fuel consumption. The data from the fuel consumption test runs were fitted with a second-order regression line and the regression line was used to reconstruct missing values. Fuel consumption at clutch RPM (about 193-195 RPM) was assumed to be 0.020 GPM.

Shaft Horsepower. Where SHP values were missing, they were reconstructed from SHP/RPM curves by a second-order regression equation. Shaft Horsepower at clutch RPM was assumed to be 15 hp where these values were missing or clearly bad.

Calculation of Fuel Mass Flow Rate

Fuel mass flow rate was calculated assuming a fuel density of 833 kg/m^3.

Calculation of Air and Water Mass Flow Rates

A Psychrometric chart for 30.00" Hg was used in these calculations. Entering the chart with the measured 36% relative humidity and 100°F (37.8°C), the absolute humidity was found to be 0.0148 kg H_2O/kg dry air, or 1.31% by total weight, and the specific volume of the air was 0.90 m^3/kg dry air.

This gives densities of 1.11 kg dry air/m^3, 0.0155 kg H_2O/m^3, and a total density of 1.1265 kg wet air/m^3.

The actual barometric pressure was 30.15" Hg. The inaccuracies in the air and water mass flow rates resulting from the difference in the specific volume of the air from the 30.00" Hg of the standard Psychrometric chart to the actual value of 30.15" Hg were deemed insignificant with respect to other experimental errors and with respect to the accuracy with which the Psychrometric chart could be read, and were thus ignored.

Determination of the Fuel-Specific Factor

Table 9 of ISO 8178-1 provides three values of the Fuel-specific Factor (FFH) for three values of Excess Air Factor. Using these, and the pair 0,0, a stepwise interpolation formula was created for FFH, which was programmed into the calculation spreadsheet. The Excess Air Percentage reported in the data was assumed equal to the Excess-Air Factor.

Correction of Dry Emissions to Wet

The exhaust concentrations of O_2, CO, NO, and NO_2 were reported in ppm by volume (dry). These were converted to ppm by volume (wet) by the procedure outlined in Section 13.2 of ISO 8178-1. The conversion factor KW is calculated independently for each test run by Equation 13 of Section 13.2. The humidity factor KW2 is a constant, equal to 0.0345 for 14.8 g/kg absolute humidity.

Calculation of the Emission Mass Flow Rates

The wet volume fractions of pollutants were converted to mass fractions of the total (wet) exhaust mass flow by the procedure outlined in Section 13.4 of ISO 8178-1.

Test Results

Only selected test results are given. The following pages show plots of NO_X on the basis of g/kw-hr and kg/metric ton of fuel. Similar plots are shown for CO. Figures 6-9 and 12 are for free running operations on both engines in two water depths, 30 feet and 20 feet. The POINT BROWER used a higher sulfur fuel than the East Coast boats. A plot of SO_2 emissions versus kw-hrs is given in Figure 12. Figures 10 and 11 show the NO_X and CO emissions versus RPM while towing. These plots show the difference in emissions when the load per engine is reduced by using a second engine while towing.

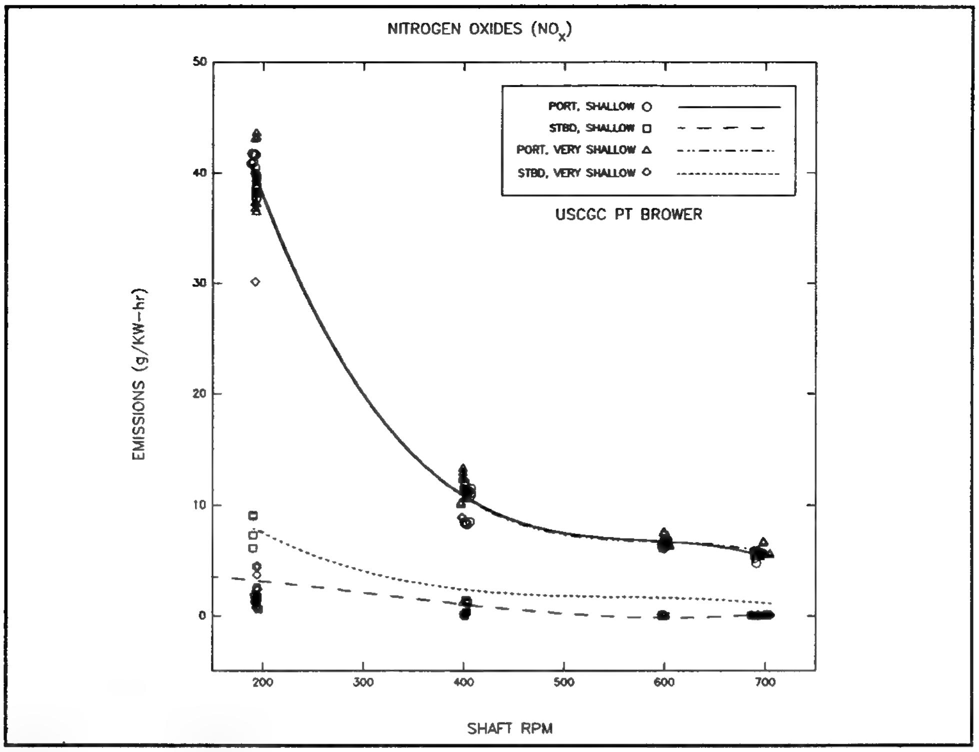


Figure 6 PT BROWER NO_X (g/kw-hr) versus Engine Speed

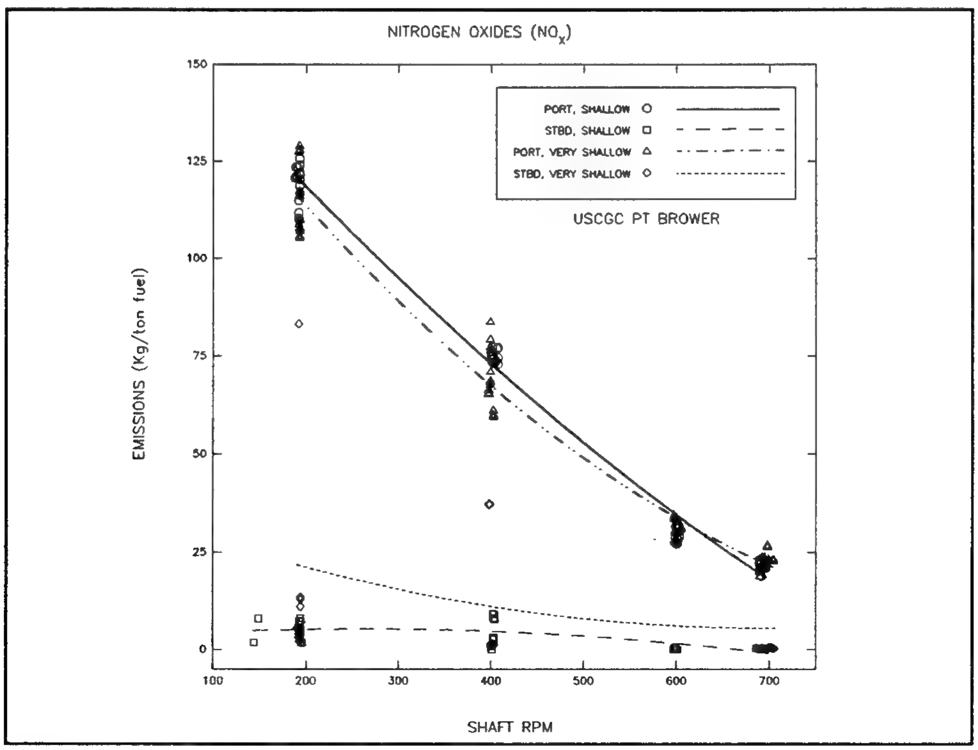


Figure 7 PT BROWER NO_X (kg/tonne fuel) versus Engine Speed

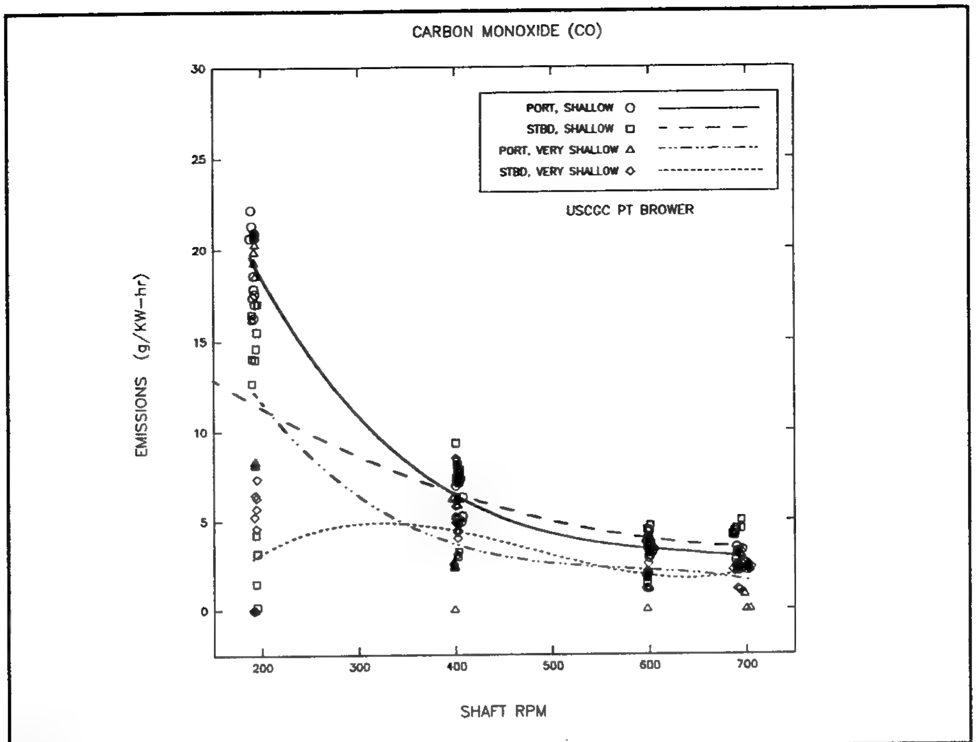


Figure 8 PT BROWER CO (g/kw-hr) versus Engine Speed

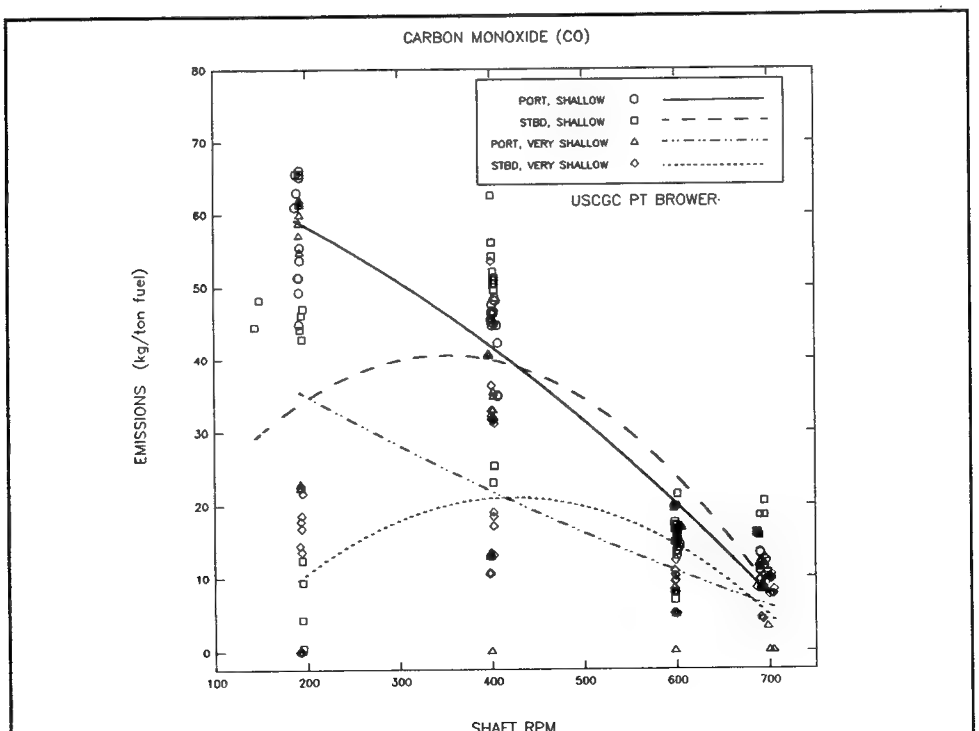


Figure 9 PT BROWER CO (kg/tonne fuel) versus Engine Speed

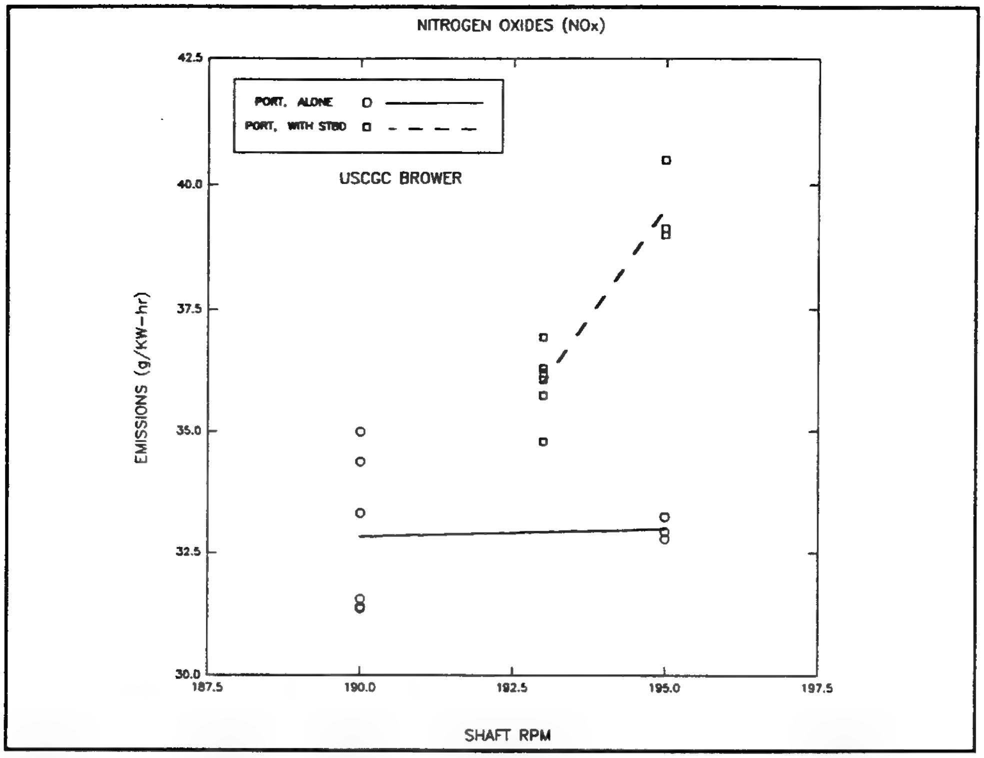


Figure 10 PT BROWER NO_X (g/kw-hr) Towing versus Engine Speed

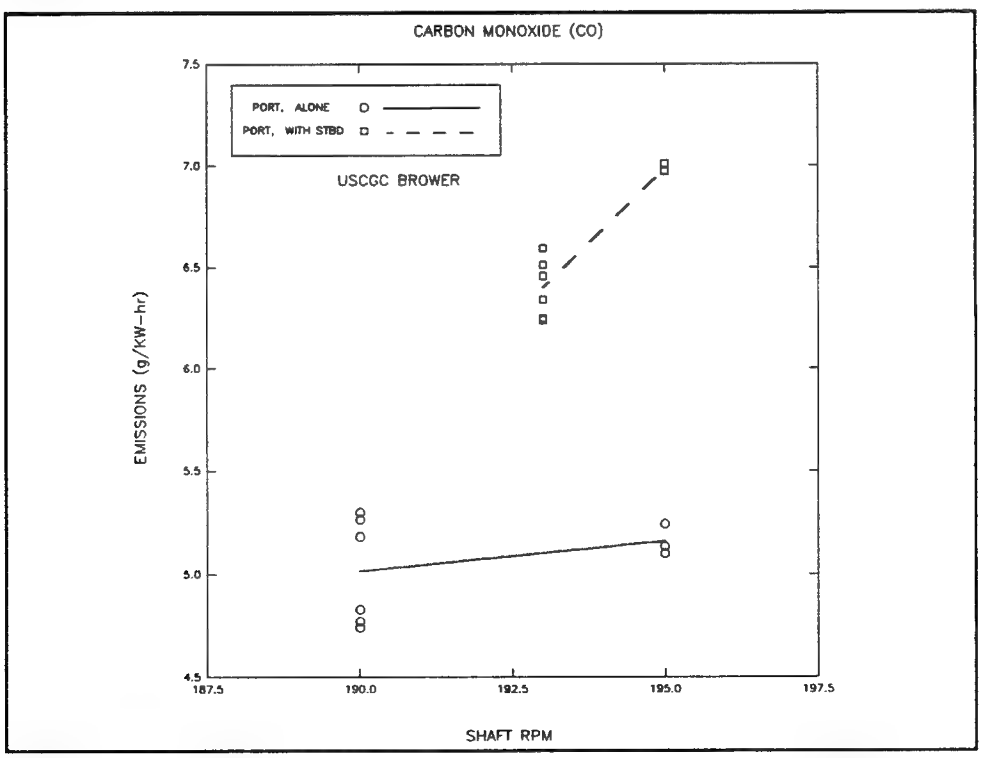


Figure 11 PT BROWER CO (g/kw-hr) Towing versus Engine Speed

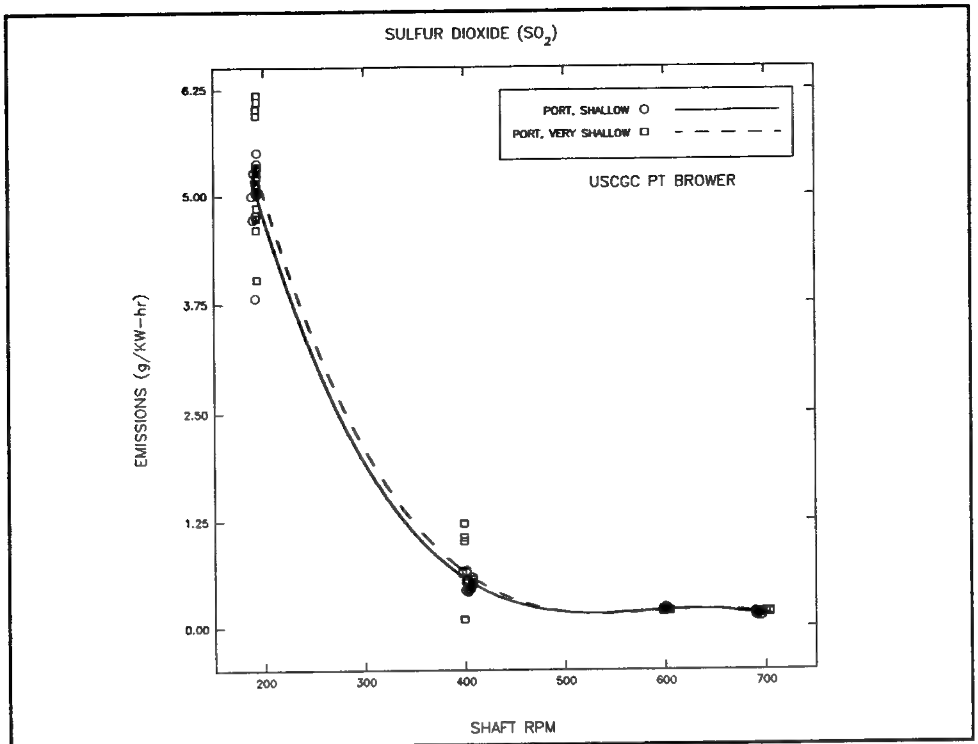


Figure 12 PT BROWER SO_2 (g/kw-hr) versus Engine Speed

4.4 USCGC POINT TURNER

The USCGC POINT TURNER operates out of Newport, RI, and was tested on November 17 -18, 1993. Data were collected in approximately 20 feet of water and in water exceeding 30 feet in depth. However, the only information on the starboard shaft is available for the deeper water.

<u>Notes on Data Analysis</u>

The data are divided into three major sections. The first section is the Starboard 30+ ft data, which includes data for the starboard shaft for tests 1.1 to 4.5, combined with the starboard "intermediate" data, denoted as tests 1.1A to 4.4A on the data sheet.

The second section is the Starboard 20 ft data, tests 5.1 to 8.4. The third section is the Port 20 ft data, tests 5.1 to 8.4.

Missing Data

A number of blocks of data were missing or clearly bad:

- All of the Shaft Horsepower data for the Starboard shaft. These data were reconstructed as described below.

- Some of the Shaft Horsepower for the Port shaft. These were reconstructed as described below.

- Some of the Fuel Consumption data for all three blocks. These were reconstructed as described below.

- Some of the Excess-Air Values for the Port 20 ft block. These were reconstructed as described below.

- Some of the SO_2 data for the Starboard 30+ ft block.

- All of the SO_2 data for the Starboard 20 ft block.

- Most of the SO_2 data for the Port 20 ft block.

Shaft Horsepower

Shaft HP values for the Starboard shaft were clearly incorrect when compared to the HP-vs-Shaft RPM curves for the POINT FRANCIS and the POINT BROWER, and for the port shaft of the POINT TURNER. A second-order regression line was fitted to the POINT TURNER's port shaft HP data and the regression line was used to reconstruct the starboard shaft data and any missing values for the port shaft.

It should be noted that the Port Shaft HP data were taken in water depths averaging 20 ft. The resulting HP/RPM curve is probably very close to that for the starboard shaft in the same depth. However, these data were also used to reconstruct the HP/RPM data for the starboard shaft in deeper water (Tests 1 to 5 and 1A to 5A).

Since a vessel's resistance at a given speed is somewhat lower in deeper water, both the Speed-vs-Shaft RPM and Shaft HP-vs-Shaft RPM relationships are different for different depths, especially at higher speeds and RPMs. There is, therefore, an additional level of inaccuracy inherent in reconstructing shaft horsepower data for the starboard shaft in the 30+ ft water depths.

The effect of the increased resistance in shallow water is twofold. First, the propeller slip is somewhat greater for a given speed, requiring a slightly higher shaft RPM to attain that speed in shallower water. Second, the shaft horsepower required to attain a given shaft

RPM increases in shallow water. While these two effects tend to cancel in terms of the HP/RPM curve, the second is predominant, and the net result is a higher shaft HP for a given shaft RPM in shallower water, with the difference more significant at higher speeds.

Fuel Consumption

Fuel consumption was generally reported for the first run of each test; however, fuel consumption values were missing entirely for several tests. Two techniques were used to fill in the fuel consumption where missing. When the RPM for subsequent runs of a test was within 2 RPM of that for the first run, and when fuel consumption was reported for the first run, that fuel consumption value was copied to the data row for the subsequent runs.

Where the shaft RPM for subsequent runs of a test differed by more than 2 RPM from that for the first run or where there was no fuel consumption value reported for the first run, the fuel consumption was reconstructed using the coefficients of a third-order regression line fitted to existing data. A separate regression was used for each of the three cases: Starboard 30+ ft, Starboard 20 ft, and Port 20 ft.

In the case of clutch RPM for the Port engine, all raw fuel consumption values were reported as "0". these were replaced by the fuel consumption at clutch RPM for the Starboard engine, which was 0.0271 gal/min.

Excess-Air Factor

A number of values of Excess-Air Factor were missing for the Port Shaft. The Excess-Air Factor is required for calculation of the Fuel-Specific Factor (FFH) which, in turn, is required for calculation of the Dry/Wet conversion factor Kw.

A first-order regression line (Excess-Air vs. Shaft RPM) was fitted to the existing data, and the coefficients for this line were used to reconstruct the missing values (Tests 5.2-5.4 and 6.5-7.1).

The Excess-Air vs. RPM plot is based on relatively few data points and the data are quite scattered, so the reconstructed data must be considered approximate. One obvious outlying point was removed before the regression line was calculated.

Unreliability of the Calculated and Plotted Results for Emissions at Clutch RPM

The values for Fuel Consumption and Shaft Horsepower at clutch RPM (0.03 GPM and 3 HP, respectively) are very low in relation to the precision of those measurements (two decimal places and whole numbers, respectively). The error in the reported data values due to quantization and round-off may be nearly 20% in each case. In addition, bias inaccuracies in the measuring equipment could cause proportionately large errors in these values. Since the Fuel Consumption and Shaft Horsepower are used to calculate the emissions per ton of

fuel and per kilowatt-hour, respectively, it is possible that the calculated and plotted values of emissions per kw-hr and per tonne of fuel at clutch RPM are highly inaccurate.

Test Results

Only selected test results are shown here. Others of less importance have been provided separately to the Coast Guard. The following pages show plots of NO_X on the basis of g/kw-hr and kg/tonne of fuel. Similar plots are shown for CO. All plots are for free running operations on both engines in two water depths, 20 feet and 30+feet. Test depths for the deeper water runs were between 30 and 48 feet.

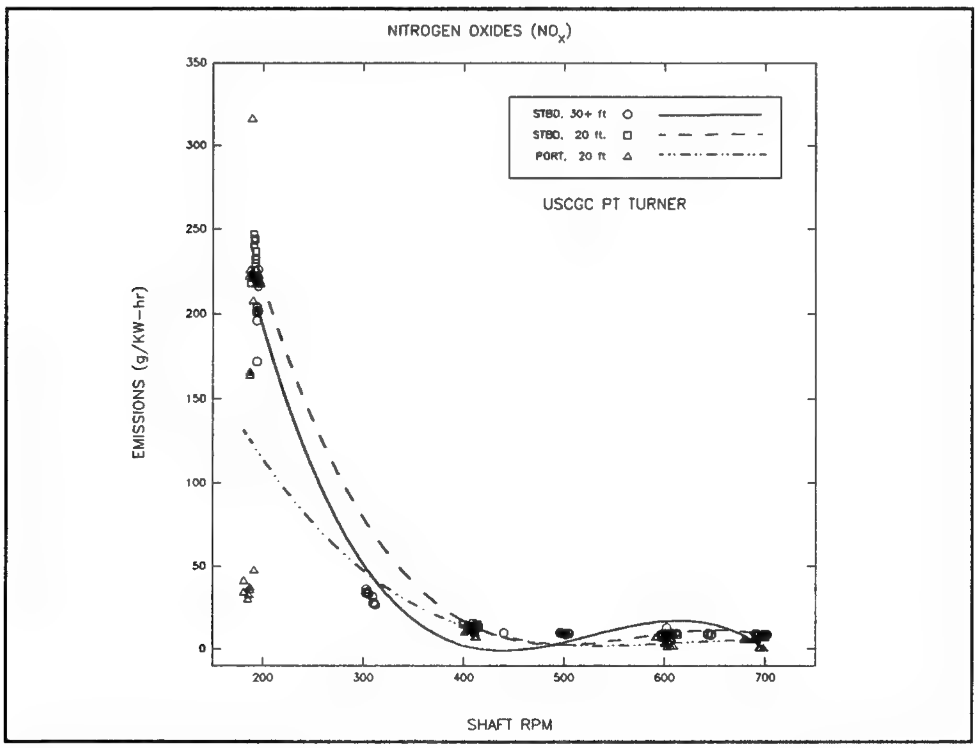


Figure 13 PT TURNER NO_X (g/kw-hr) versus Engine Speed

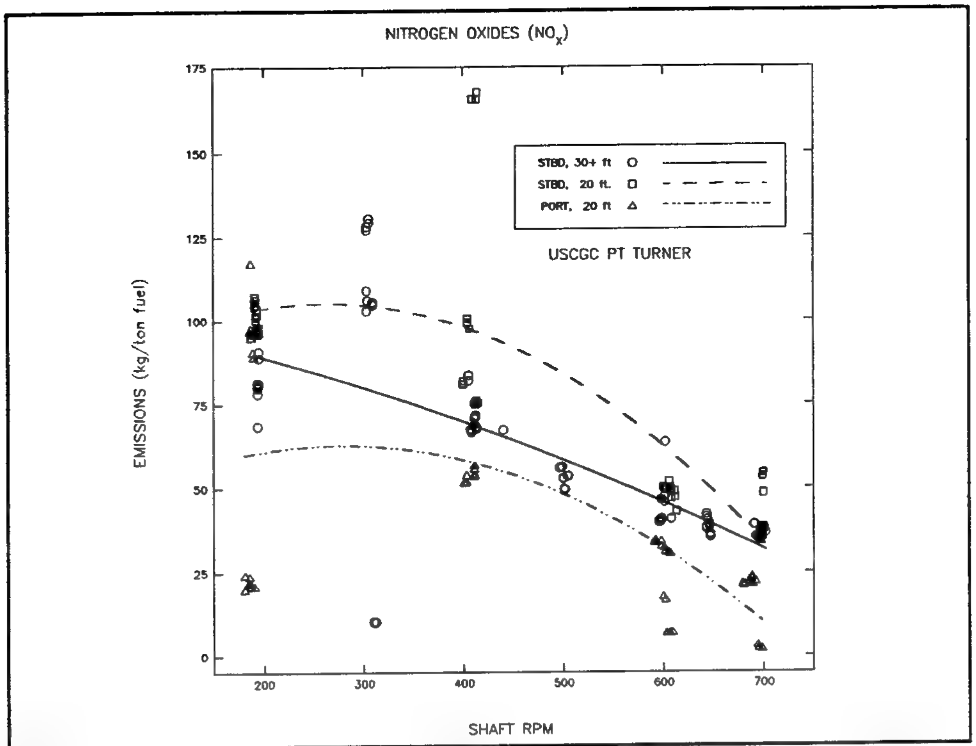


Figure 14 PT TURNER NO_X (kg/tonne fuel) versus Engine Speed

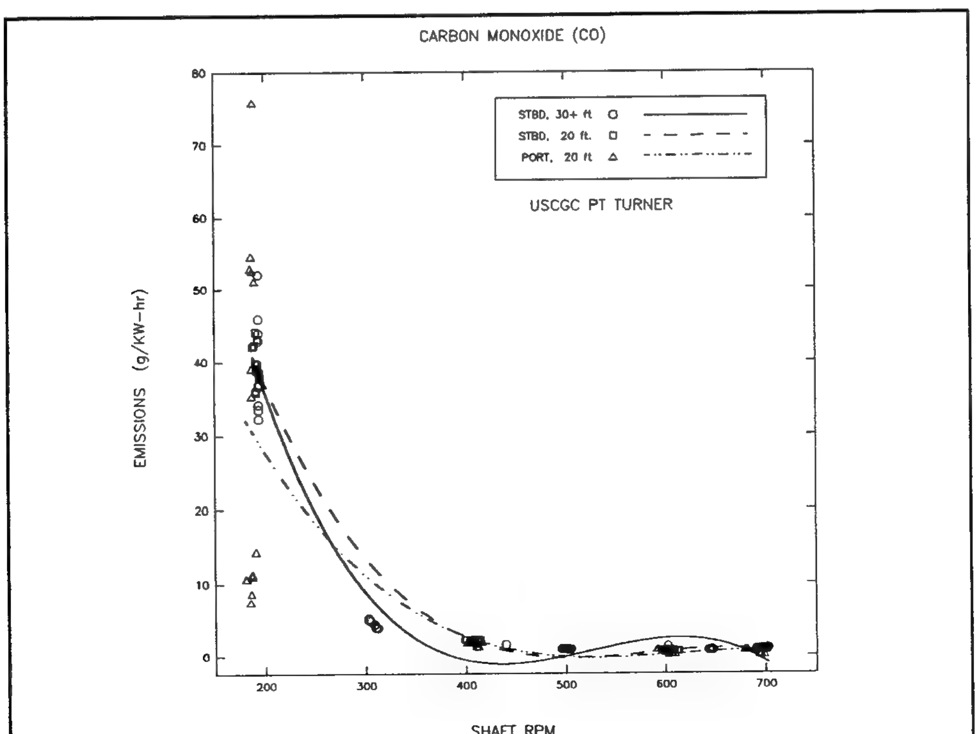


Figure 15 PT TURNER CO (g/kw-hr) versus Engine Speed

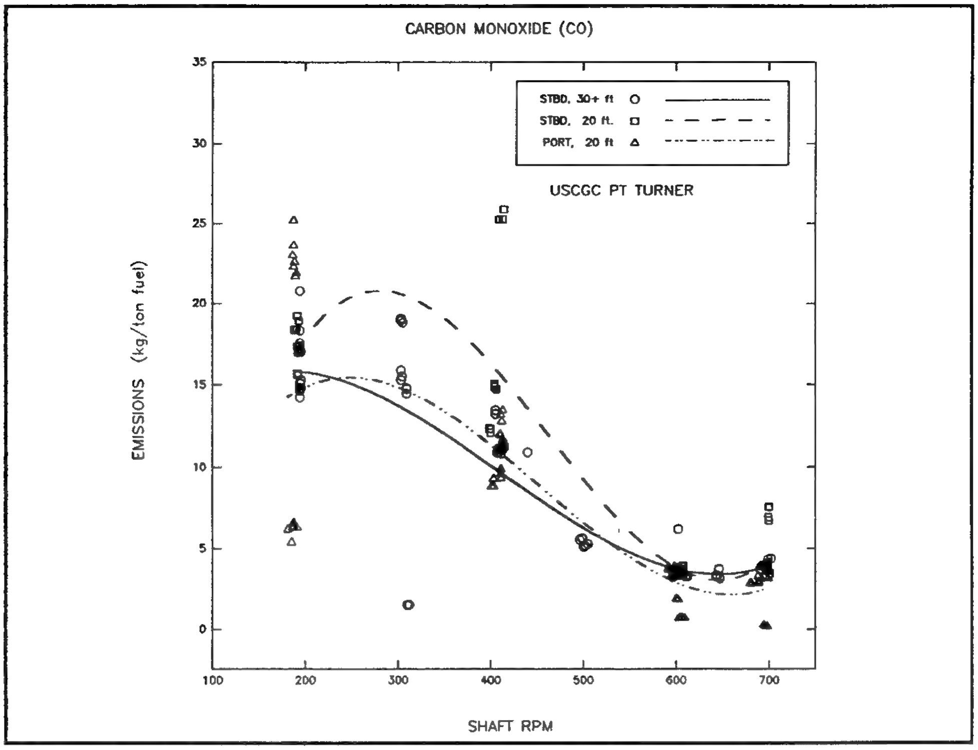


Figure 16 PT TURNER CO (kg/tonne fuel) versus Engine Speed

4.5 Comparison of Results from Shipboard Tests

Only the NOx and CO results will be compared as these are the principal emissions of interest. The SO_2 emissions are largely dependent on the fuel quality available and not on the engine. Figure 17 shows the raw dry NO_X volume measurements in 30 feet of water. Data from both engines on the POINT FRANCIS are shown. Only single engine data from the POINT BROWER (port) and POINT TURNER (stbd) are available. Figure 18 shows the raw CO data for the same operating conditions. Data for the starboard engine on the POINT BROWER has been included.

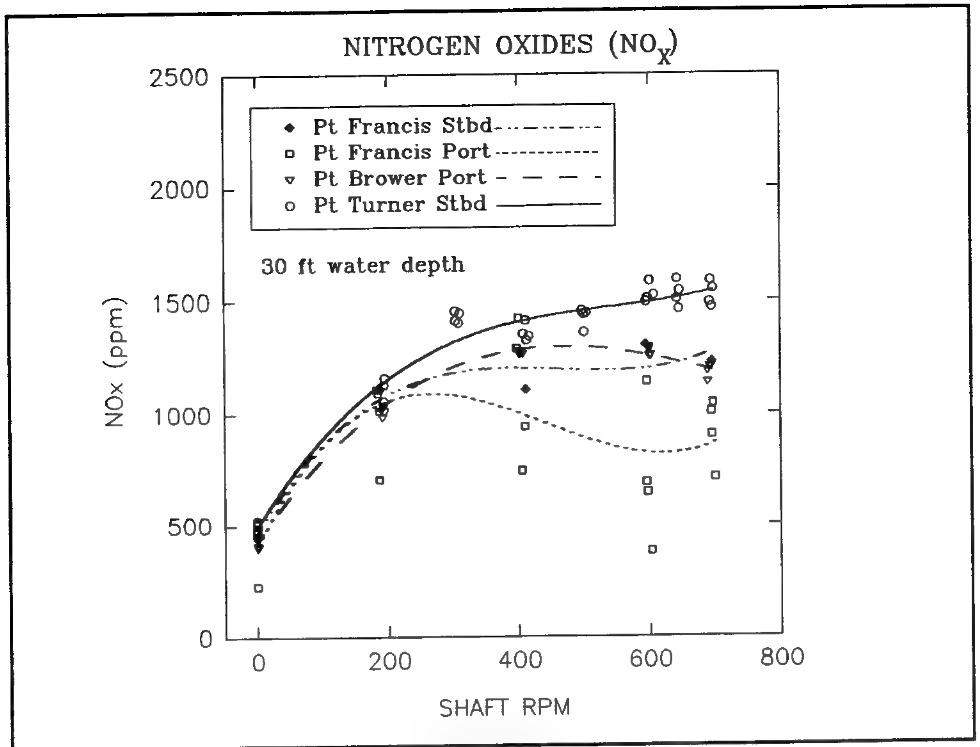


Figure 17 Combined NO_X Results (Raw Data - Not Normalized)

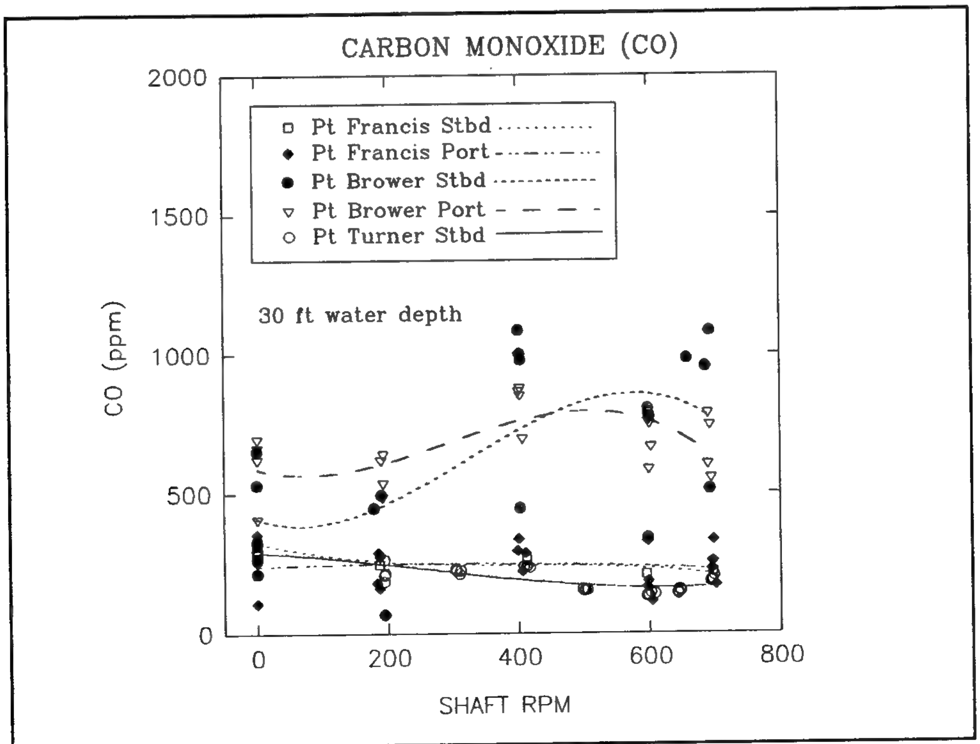


Figure 18 Combined CO Results (Raw Data)

5 CONCLUSIONS FROM SHIPBOARD TESTS

5.1 USCGC POINT FRANCIS Tests

There was no significant difference in emissions between the shallow and deep water tests. The shallow water tests were run in 30 feet of water which is still relatively deep for the size vessel tested. Therefore, no significant differences in propeller loading or in emissions would be expected.

As with all the ship tests, the emission levels for NO_X and CO drop rapidly until about 400 SRPM at which point they begin to level out on a g/kw-hr or a kg/tonne basis. For this cutter, the NO_X values level off at approximately 10 g/kw-hr or 25 kg/tonne of fuel; CO levels off at 2 g/kw-hr or 6 kg/tonne of fuel.

5.2 USCGC POINT BROWER Tests

The emission curves for the POINT BROWER follow a similar pattern to those of the POINT FRANCIS. However, the variations between the port and starboard engine are wider for NO_X. The NO_X emissions level off at about 3 g/kw-hr for the starboard engine and about 8 g/kw-hr for the port engine. Both values are lower than measured for the POINT FRANCIS. CO leveled off at approximately 3 g/kw-hr.

The shallow water tests and towing tests indicated that emissions of CO are reduced as engine load increased. The shallow water tests showed no difference in NO_X output but the towing tests indicate a decrease in NO_X with one engine operation. NO_X output during towing was nearly equal to NO_X output while free running at the same SRPM. However, CO output was much lower while towing than while free running at the same SRPM.

The calculated SO_2 output leveled off similar to CO and NO_X. The value after it had leveled off was approximately 0.5 g/kw-hr. There was no measurable difference in shallow versus deep water. This was expected because the SO_2 output depends primarily on the fuel used.

5.3 USCGC POINT TURNER Tests

The POINT TURNER tests showed no significant differences in emissions between tests in 20 feet of water and those in deeper water. After leveling off NO_X averaged 10 g/kw-hr and CO averaged 2 g/kw-hr, identical to the POINT FRANCIS results and similar to the POINT BROWER results.

5.4 Combined Results

Referring to Figures 17 and 18, there was little difference between the NO_x output of the three cutters. POINT FRANCIS produced slightly less NO_x but the difference between the two engines on the POINT FRANCIS was of the same order of magnitude as the reduction in NO_x observed between the POINT FRANCIS and the other two cutters. Figure 18 shows that the POINT BROWER was producing significantly more CO than the other two. Both engines on the POINT BROWER were higher. This may be due to fuel differences between the West and East Coast boats or due to the fact that POINT BROWER's engines had more hours on them since installation. However, the cause of the difference can not be ascertained from the data.

6 EXPERIMENTAL DESIGNS FOR CFR ENGINES

Co-operative Fuel Research (CFR) engines are one cylinder engines that have been used for fuel research and testing for more than half a century. They are specified in Federal regulations for testing fuels sold commercially. There is a diesel and a spark ignited version of the CFR engine. The Coast Guard Academy has one of each type in its mechanical engineering laboratory. The diesel version is used in industry to test the cetane rating of diesel fuel. The octane rating of gasolines is determined using the spark ignited version. An experimental design was developed for each of the two engines to measure exhaust emissions over as much of the engines' operating range as possible. The experimental designs for the diesel and spark ignited engines are attached as appendices C and D, respectively.

6.1 Diesel CFR Engine Experimental Design

The dependent variables for this design and for the spark ignited engine design were specified in the statement of work. These consisted of the measured gaseous emissions of NO, NO_2, SO_2, CO, CO_2, and O_2.

The independent variables were chosen after consulting with the CFR engine operators at the the Coast Guard Academy and with Waukesha Engine Division of Dresser Industries, the manufacturer of the CFR engine. The tests proposed require the engine to be operated outside its normal operating range and no one was sure whether or not the engine would run with the various combinations of independent variables proposed. As a result, independent variable ranges were proposed in the experimental design with the recommendation that preliminary experiments be performed to determine if the engine could be made to run at the extremes of the ranges. The independent variables proposed, together with the proposed operating ranges are as follows:

Test Variable	Low Level	Mid Level	High Level
Engine RPM	600 /min	1200 / min	1800 /min
Engine Torque	1.5 ft-lbs	8.0 ft-lbs	14.5 ft-lbs
Compression Ratio	10:1	20:1	30:1
Inlet Air Restriction (Orifice size)	0.75 inch	1.4 inch	2.049 inch
Injection Timing	16° BTDC	12° BTDC	8° BTDC
Fuel Type	Diesel only	60/40 Diesel/ Natural Gas	20/80 Diesel/ Natural Gas

All terms in the emission equations through second order terms were sought. With the 6 independent variables proposed, there are 28 second and lower order terms. With three levels of the independent variables, only second order terms can be determined with accuracy.

A number of experimental designs were evaluated as discussed in Appendix C. A face-centered cube design was recommended because it permitted collecting data at the corner points of the hypercube and required a reasonable number of test runs when used with a half fraction design on six variables. The two recommended analyses approaches, a stepwise regression analysis or a nonlinear regression analysis, do not require that the data points be precisely located so the data points could be adjusted inward towards the center of the hypercube if the engine would not operate at any combination of independent variables. In all, this approach required 50 experimental runs. This number included half the corner points (32), 6 repeats of the center of the cube, and 12 points in the center of the cube faces. This number of experimental runs permits calculating the 28 coefficients in the regression equations with 22 additional degrees of freedom.

6.2 Spark Ignition CFR Engine Experimental Design

The spark ignited CFR engine design was very similar to the diesel design except that there were fewer independent variables. Two fuels were required to be tested, gasoline and propane. Engine changes are required to operate on the two fuel types so it was not possible to make fuel type a continuous variable of the experiment as was done with the diesel engine. As a result, two experiments, one for each fuel type, are required. Each of these experiments has 5 independent variables as follows:

Test Variable	Low Level	Mid Level	High Level
Engine RPM	600 /min	1200 / min	1800 /min
Engine Torque	1.5 ft-lbs	8.0 ft-lbs	14.5 ft-lbs
Compression Ratio	5:1	10:1	15:1
Inlet Air Restriction (Orifice size)	0.75 inch	1.4 inch	2.049 inch
Spark Timing	25° BTDC	15° BTDC	5° BTDC

The regression equations with 5 independent variables contain 21 second order and lower terms. A half fraction design on 5 variables consists of 32 test runs. This is a minimal number when trying to estimate 21 coefficients. It was recommended that a full

fractional design be used instead. Such a design has 32 corner points, 6 repeats of the cube center, and 10 mid points on the faces of the cube for a total of 48 test runs. The full fractional design provides 27 degrees of freedom rather than 11 and provides better statistical accuracy for estimating coefficients in the reqression equations.

7 DIESEL CFR ENGINE TEST RESULTS

As discussed above, there was uncertainty concerning engine performance with the levels of the independent variables chosen in the experimental design. The R&D Center conducted preliminary tests on the engine and altered the variable levels. It was also found that the inlet air could not be regulated well with the use of orifices in the intake air line. It was decided to drop this variable and test the engine with the 5 remaining independent variables. A full fractional design in 5 variables is very similar to a 6 variable half fractional design. The only change that had to be made was deletion of the two data points corresponding to the mid points on the cube faces at the maximum and minimum levels of the variable deleted. The resulting experimental design had 48 data points. The final design as tested was:

Test Variable	Low Level	Mid Level	High Level
Engine RPM	800 /min	1300 / min	1800 /min
Engine Torque	2 ft-lbs	6 ft-lbs	10 ft-lbs
Compression Ratio	13:1	16:1	19:1
Injection Timing	21° BTDC	16° BTDC	13° BTDC
Fuel Type	Diesel only	60/40 Diesel/ Natural Gas	20/80 Diesel/ Natural Gas

The tests were run at the Coast Guard Academy during the summer of 1994 over a two-day period. Data were analyzed using a statistical package called SigmaStat. Two analyses were done. The first used a nonlinear regression analysis technique based on the Marquardt-Levenberg algorithm. This required several runs to determine the value of regression equation coefficients. All coefficients were included in the first run. After that, coefficients that had little impact on the results were eliminated after each run until a final set of coefficients was obtained. This procedure never puts coefficients back into the equation after others have been eliminated. The second analysis modeled the second order terms as new variables in the equation. This permitted a linear stepwise regression technique to be applied. A forward stepwise regression analysis was conducted. In this procedure, the equation is first estimated by a constant and then terms are added step by step based on the coefficients that have the greatest impact on the result. This procedure also looks at redundant coefficients after each step and may remove some that were added previously. In some cases the results were different between the two analyses. The stepwise regression is considered the more accurate because it is continually adding and removing terms to get the best fit. The results of the stepwise analysis are reported below.

The analyses were made using normalized independent variables to maintain a constant variance over the experimental space. This also made the analyses faster and more accurate within the experimental space. The variables were transformed so that the middle value was always zero and the high and low values were 1 and -1, respectively. After the coefficients of the transformed variables were determined, the actual equations were created by substitution of variables.

In the equations that follow the following independent variables are used:

RPM - Engine RPM - Range 800 to 1800

T - Engine Torque in ft-lbs - Range 2 to 10

CR - Compression Ratio - Range 13 to 19 (13:1 to 19:1)

I - Injection Timing ° BTDC - Range 13 to 21

FR - Fuel Ratio (fraction diesel) - Range 0.2 to 1.0

The formula obtained for NO in ppm is:

$$NO = -2022.48 - .156xRPM + 117.35xT + 100.703xCR + 31.858xI - 104.741xTxFR \ldots$$
$$+ 2125.194xFR - 93.547xCRxFR$$

The formula for NO_2 in ppm is:

$$NO_2 = 135.532 -.107xRPM + 15.971xT + 22.738xI - 93.145xFR - 2.402xTxI$$

The formula for NO_X in ppm is:

$$NO_X = -2631.817 - .277xRPM + 191.143xT + 125.524xCR + 75.581xI - 6.337xTxI \ldots$$
$$-91.242xTxFR + 2383.308xFR - 114.741xCRxFR$$

Note that NO_X was determined from a regression analysis on the NO_X data. Therefore, the equation obtained is not the sum of the NO and NO_2 equations. This sum could be used as another estimate of NO_X.

The formula for O_2 in percent is:

$$O_2 = -14.734 - .000661xRPM - 1.117xT - 6.79xFR + .2988xTxFR - .0527xCRxI \ldots$$
$$+3.305xCR + .844xI + .3775xCRxFR - .000158xRPMxT - .0823xCR^2$$

The formula for CO in ppm is:

$$CO = 1416.559 - 36.760xT - 356.438xFR$$

Note: the values for CO were also correlated to the run number indicating a time dependence of the readings. This indicates an instrument saturation problem. This time dependence has been removed from the above equation.

The formula for CO_2 in percent is:

$$CO_2 = 8.798 - .007183xRPM + .699xT + .00015xRPMxT - 2.252xFR \ldots$$
$$+ .00000266xRPM^2 + .00124xRPMxFR$$

Excess air, SO_2, and Combustion gas were also measured. The SO_2 and combustion gas readings were low and erratic and could not be correlated with the independent variables.

The formula for Excess Air in percent is:

$$\text{Excess Air} = 332.593 - .0414xRPM - 39.562xT - 4.673xI + 12.562xFR \ldots$$
$$+ .00268xRPMxT + 1.056xT^2 + .404xTxI$$

8 CONCLUSIONS FROM DIESEL CFR TESTS

The significance of the tests on the diesel CFR engine is that this is the first test known that varies the level of more than one independent variable at a time while measuring emissions. This permits the effect of interdependencies between variables to be detected which could not be found in a single variable at a time test approach.

This section discusses the findings with regard to NO_X and CO which constitute the worst emissions. Other emissions could be analyzed similarly.

$\underline{NO_X}$

An idea of the importance of each term in the NO_X equation can be obtained by looking at the magnitude range of each constituent in the equation. The maximum and minimum values for the test range are shown.

	Minimum Value	Maximum Value
Constant	-2631.8	-2631.8
-.277xRPM	-221.6	-498.6
191.143xT	382.3	1911.4
125.524xCR	1631.8	2385.0
75.581xI	982.6	1587.2
-6.337xTxI	-164.8	-1330.8
-91.242xTxFR	-36.5	-912.4
2383.308xFR	476.7	2383.3
-114.741xCRxFR	-298.3	-2180.1

Assuming we would like our engine to produce as much power as possible there is little we can do about reducing torque and RPM. The equations can be simplified by setting both of these at the maximum values.

$$NO_X = -1219 + 125.524xCR + 12.21xI + 1470.89xFR - 114.741xCRxFR$$

From this equation it is clear that the injection timing should be as low as possible (as close to TDC as possible). If we set its value at 13 the equation can be reduced further. This is the preferred setting for engine performance anyway.

NO_x = -1060.3 + 125.524xCR +1470.89xFR - 114.741xCRxFR

This leaves only two independent variables in the equation, fuel ratio and compression ratio. Since fuel ratio varies from .2 to 1, the magnitude of the last term is always less than or equal to 114.741xCR which causes less of a reduction than the second term causes an increase. Therefore, reducing the compression ratio will reduce NO_x. Setting the compression ratio value to 13 yields the formula:

NO_x = 571.5 - 20.743xFR

This is an interesting result as it indicates the fuel ratio has almost no effect on NO_x emissions with straight diesel giving the best result. However, a higher compression ratio may be needed for better fuel economy. The formula using a compression ratio of 19:1 is:

NO_x = 1324.7 - 709.19xFR

Here the effect of using straight diesel is more pronounced. Note also that if straight diesel is used that NO_x increases by 12 percent between the low and the high compression ratio. These effects are shown in the following figure covering the range of fuel ratios and compression ratios tested.

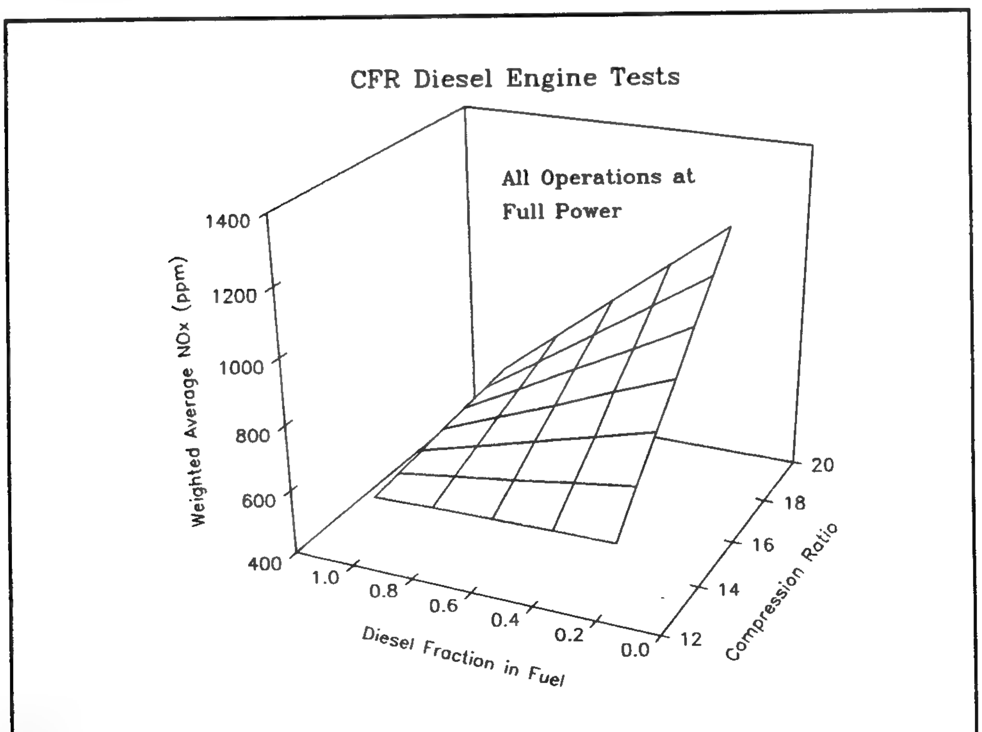


Figure 19 CFR Engine Full Power

Coast Guard cutters do not operate all the time at full power. The following discussion is based on a set of five power and RPM combinations (operating points) for the CFR engine that simulate a propeller curve for the engine. The values of RPM and torque used are:

Operating Point	RPM	Torque
1	800	2 ft-lbs
2	1050	3 ft-lbs
3	1300	4.8 ft-lbs
4	1550	6.4 ft-lbs
5	1800	10 ft-lbs

By taking a weighted average of emissions at these 5 operating points, ship operations at less than full power can be simulated in a manner similar to the previously discussed shipboard tests. The weighted average NO_x results for the CFR engine were calculated for 3 different combinations of operating points as follows:

	Weightings		
Operating Point	Higher Power Operations	Equal Weighting	Lower Power Operations
1	0	.2	.4
2	.1	.2	.3
3	.2	.2	.2
4	.3	.2	.1
5	.4	.2	0

The simulated propeller curve and the above weightings were used to construct the following three plots that show the weighted average single number NO_x value versus the fraction of diesel in the fuel and the compression ratio. All these plots were constructed for a 13° BTDC injection timing. The net increase in NO_x as injection timing is increased to 19° is:

$$\Delta NO_x = 453.486 - 38.022\text{x}torque$$

The maximum torque tested was 10 ft-lbs so the net increase will always be positive. Therefore, the 13° BTDC injection timing always gives the lowest NO_x emissions within the range tested.

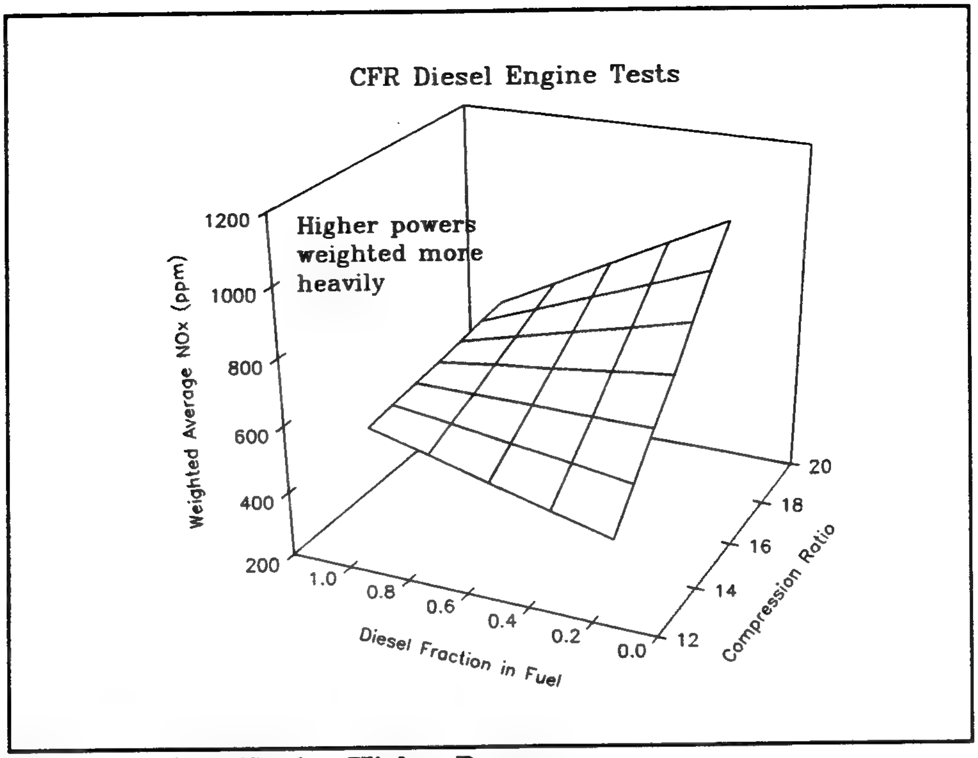


Figure 20 CFR Engine Higher Powers

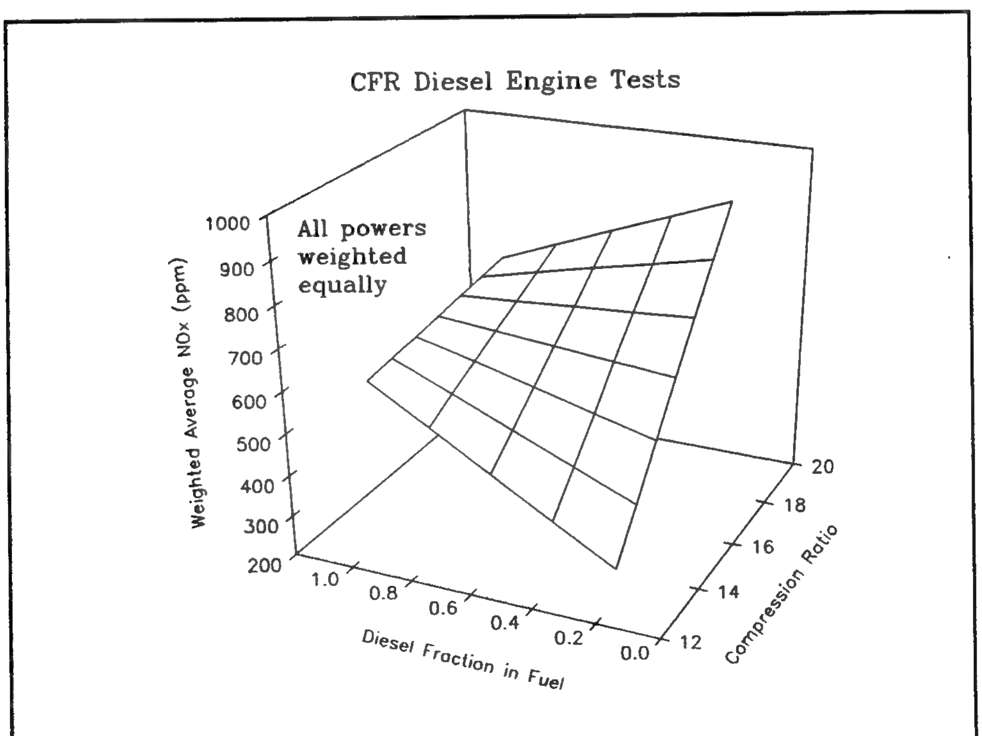


Figure 21 CFR Engine Equal Weighting

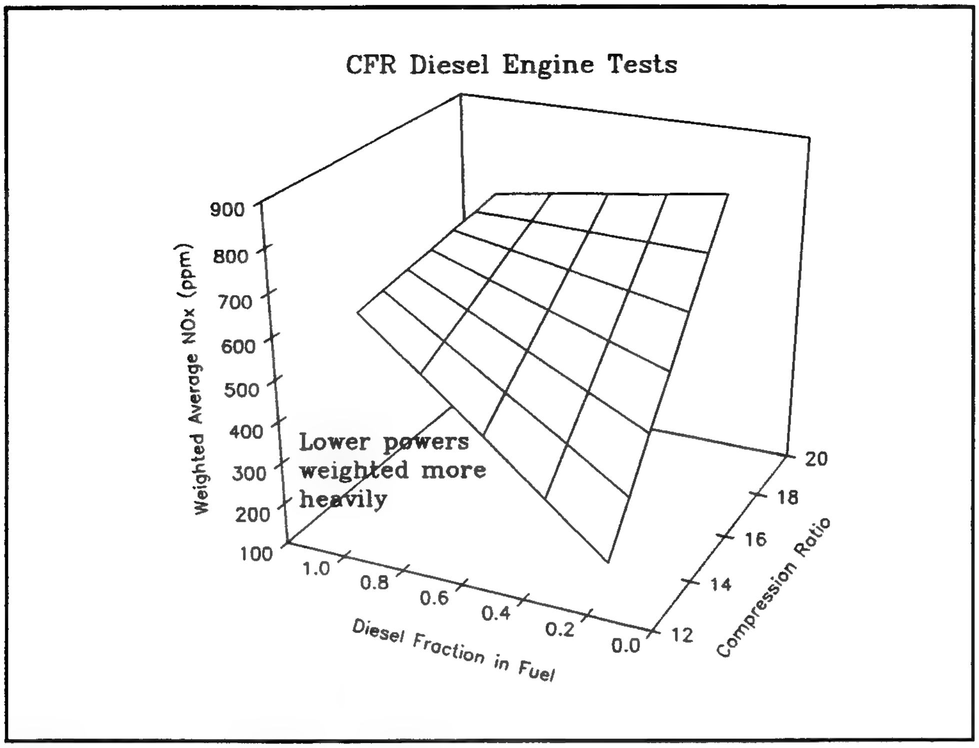


Figure 22 CFR Engine Lower Powers

These figures show that there is an advantage to reducing the diesel content when ship operations include lower powers. The more time spent at lower powers, the greater the advantage to using some natural gas. Also, compression ratios must be reduced to make the use of natural gas effective.

CO

The equation for CO is much simpler than for NO_X and the best values can be seen from inspection. The equation is repeated below:

CO = 1416.559 - 36.760xT - 356.438xFR

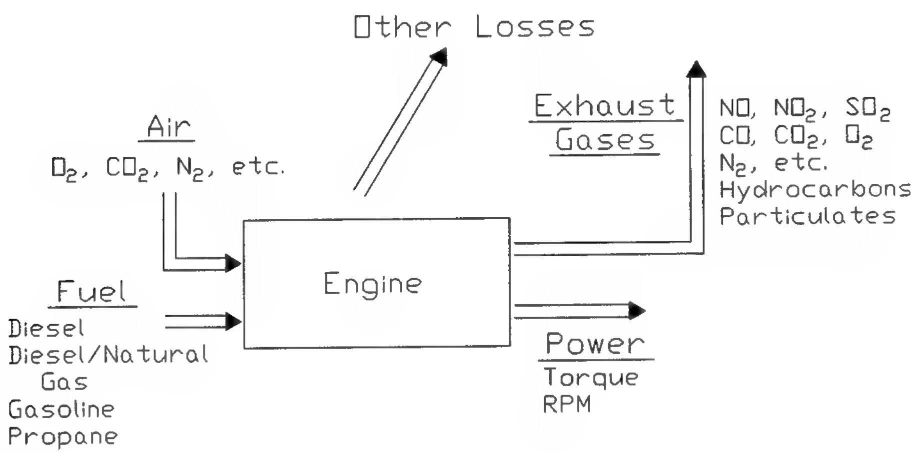
Both high torque and a high diesel ratio are beneficial towards reducing CO. Adding natural gas to the diesel fuel will increase CO output. The reduction in CO with torque is rather surprising because more fuel is being added at a given RPM. This results in more fuel being mixed with the same amount of oxygen so intuitively less of the carbon should combine to form CO_2 and more CO should be emitted. It is interesting to note that this same result was observed during shipboard tests where more load, i.e., more torque, resulted in less CO in the exhaust.

Appendix A

ENGINE EMISSION TEST VARIABLES

Introduction

The figure below shows the principal inputs and outputs for a diesel engine when viewed as a free body. This diagram illustrates the main external factors that have to be considered in the design of this experiment. "Other losses" includes the heat lost to the engine room and heat transferred to cooling water or oil. These losses are not important in the engine emissions tests so long as oil and water temperatures are maintained constant. Each of the factors shown is discussed in more detail in the sections that follow.



Additional factors arise within the engine itself. Many of these are fixed because of the engine design. The engine factors include compression ratio, injection timing and duration, injector size and spray pattern, injection pressure, combustion chamber shape, condition of filters and general engine wear, blowby past the piston rings, cylinder wall and piston temperatures, and air/fuel ratio. All of these could affect the engine emissions.

The constituents of the fuel used, the air/fuel ratio, and the peak firing temperatures are expected to have the greatest effect on emissions. The fuel contributes most of the nitrogen in NO_x and the sulfur, carbon and hydrogen in exhaust compounds. Some of the CO_2 in the exhaust along with the oxygen and nitrogen comes from the inlet air. Particulates in the exhaust are mostly due to ash in the fuel. The amount of CO formed depends on the amount of excess air present. NO_x formation is associated with high peak flame temperatures and the amount of nitrogen in the fuel.

Air

Ideally, we would like to be able to charge the cylinder with pure oxygen on each firing cycle and inject all the fuel that could combine with that much oxygen. If this could be done, engines could be made very small for a given power. Unfortunately, air contains only about 21% oxygen and it isn't practical to scavenge the cylinder completely of burnt gases and replace these with new air on each cycle. As a result, much more air must be pumped through the engine by the pistons than is needed for combustion. Some of the intake air also mixes with the exhaust gases while both the intake and exhaust valves are open and leaves through the exhaust ports.

Volumetric efficiency in a 4 stroke engine (scavenging efficiency in a 2 stroke) measures how much of the ideal charge of air actually gets into the cylinder on each cycle. If the swept volume of the cylinder could be charged with new air at atmospheric pressure, volumetric efficiency would be 100%. Typical diesels have 80 - 90% volumetric efficiency. The volumetric efficiency of the CFR engines is probably a lot lower. The time available to recharge the cylinder on a rapidly turning engine is short. The air flow must be rapid and there are significant pumping losses in the intake manifolds, filters, and intake valves that prevent all the air desired from reaching the cylinders. These pumping losses are what limit the volumetric efficiency. Intake valve timing is also important as it determines how much time is available for recharging the cylinder with air.

Injection of fuel into the cylinders is not 100% efficient either. It isn't possible to burn the fuel with a stoichiometric quantity of oxygen because of the difficulty in bringing all the fuel molecules in contact with oxygen molecules. The goal is to get as much oxygen as possible into the cylinder during the recharge period so the fuel has a better chance of contacting oxygen molecules when injected. The amount of air (oxygen) that can be charged in the cylinder depends on the air's specific volume which is determined by its pressure and temperature. Since air is more dense at lower temperature, intercoolers are sometimes installed in the air lines to cool the air before it gets to the cylinders. The pressure is often increase by turbochargers or blowers to also increase the density and get in more oxygen. Intercoolers are often used after turbochargers because compressing the air increases its temperature.

The amount of oxygen in the air is important, of course. If the charge air comes from an oxygen deficient atmosphere, the engine won't produce as much power. Water vapor in the air also reduces the amount of oxygen and changes the air density.

Most of the "air" factors mentioned can not be set by the experimenter. The only factor that can be altered with the CFR engine is the air/fuel ratio (mixture ratio on the spark ignited engine). This can only be controlled approximately if other factors such as RPM and torque are fixed. At a given RPM, the air flow can be controlled by adding flow restriction to the intake air line in the form of an orifice. Two or three different levels flow restriction should be used

as one variable in the experiment. Other factors such as percent of oxygen in the air, air temperature, air pressure, humidity, and flow rate should be measured and reported.

Fuel

Four different fuels have been specified for the tests; for the diesel engine - diesel and a diesel/natural gas mixture; for the spark ignited engine - gasoline and propane. Current plans are to conduct an individual test series with each fuel type. An alternative is to make the two fuels for each engine another variable in a single test series. The constituents of each test fuel should be measured and reported. Of particular importance are the quantities of carbon, hydrogen, water, sulfur, and ash in the fuels used.

Fuel additives could also be included as a variable. The fuel variable would then be the fuel alone versus the fuel with one or two amounts of additive. The entire test series would need to be repeated for each different additive of interest.

I recommend fixing the engine RPM and torque at two or three levels each. At each of the resulting test points the amount of fuel is fixed by what is needed for the engine to generate the desired torque. This quantity of fuel must be measured and reported. The mixture ratio should also be noted on the spark ignited engine. However, the fuel rate should not be an independent variable. Note that the amount of air drawn into the engine at a given RPM is set by the intake restrictions and engine design. The amount of fuel required is set by the torque. Therefore, the air/fuel ratio (mixture ratio) will vary somewhat at each of the test points. This is what happens in a real engine and I feel it is the best way to conduct tests on the CFR engines, as well.

Exhaust Gases

What goes into the engine has to come out so there is little control over exhaust variables. We can only measure them. The exception is exhaust back pressure. Back pressure could be changed by inserting restrictions in the exhaust line much as in the intake line. In shipboard installations, the rule has always been to reduce exhaust back pressure to increase engine power. Increased back pressure makes the engine less efficient and should cause increased pollutants. Because the present policy results in the least pollutants, I don't see a need to test the engines in a worse condition unless it is to emphasize the importance of low back pressure from an emissions standpoint.

The characteristics of the engine exhaust are the dependent variables of the experiments. These include the constituents of the exhaust - NO, NO_2, SO_2, CO, CO_2, and O_2, as well as hydrocarbons and particulates, exhaust back pressure, exhaust temperature, and flow rate. The last three of these measurements are needed to determine the volume of gas leaving the engine so quantities of pollutants entering the atmosphere can be determined.

Engine Power

Engine speed and torque have significant effects on emissions. Both should be independent variables for the experiments. Two or three levels of both speed and torque should be tested. The lowest speed should be near idle and the upper speed should be near the engine rated speed. The lower torque can be set arbitrarily. It should be between 0 and 50% of the highest torque used. The upper torque limit will be governed by the lower of the smoke limiting torque at the low RPM or the engine power limits at the upper RPM. The high power may be limited by any of a number of factors including enough air flow, exhaust temperatures, cylinder firing pressures, etc. The upper limit on torque will be affected by the other independent variables chosen. It is important to chose the highest torque that can be tested with all input variable combinations. Some preliminary screening will be required to determine what the worst cases are and their associated torque values.

Engine Variables

The number of engine variables that could affect emissions is almost endless. However, only a few of them are likely to have a significant effect. In the top group are such factors as compression ratio, injector timing or spark timing, injection duration, injector size and injection pressure, combustion chamber shape, inlet and exhaust valve timing, and engine condition. Several secondary factors that might have an effect include lubricating oil type, piston blowby, cylinder wall temperature and piston temperature.

In the top group, combustion chamber shape and engine condition are not controllable. The injector size, injection duration, and injection pressure are also fixed by engine design. Inlet and exhaust valve timing could only be varied with difficulty as these are set by cams on a camshaft. We could change the point at which the valves start to open by jumping one or more teeth on the gear drive but this might cause engine damage and would have to be studied. The amount of opening and the duration of opening is controlled by the cams and could only be change by having new camshafts ground. The two remaining factors, compression ratio and injector or spark timing, can and should be included as independent variables in the experimental design. These are the two which likely have the most significant effect, fortunately. Both are likely to affect the peak flame temperature during firing and hence the formation of NO_x. On the spark ignited CFR engine, spark advance is linked to the compression ratio setting. The engine will need to be modified to allow the two to be adjusted independently.

In the secondary group, lubricating oil type and cylinder wall temperature (jacket water temperature) can be varied but these probably have minimal effect on emissions. I don't recommend including them. Piston blowby is partly a design factor and partly a maintenance factor. Piston temperature is controlled by the engine design.

Summary

Based on the above discussion, the following independent variables are recommended for the tests on the CFR engines. Since the number of variables is fairly large, a screening

experiment would be useful to help reduce the number of variables before a more detailed experiment is conducted.

1. Two or three levels of inlet air flow restriction set by using different intake orifice sizes.

2. Four different fuel types are being considered. The two diesel engine fuel types can be considered as separate experiments or as two levels of the same experiment with fuel type as an independent variable. The same applies to the two spark ignition engine fuels.

3. Optional - Test with and without fuel additives. Each different additive represents a separate experiment.

4. Optional - Two or three levels of exhaust back pressure set by using orifices in the exhaust line.

5. Two or three levels of engine torque. This can be controlled either by letting the dynamometer hold the RPM constant while the operator increases fuel (mixture ratio on the spark ignited engine) until the desired torque is indicated or by holding the torque constant while fuel is added until the desired RPM is reached. The former method is preferable. If three levels are used, the middle point should be half way between the other two. Three levels will provide an indication is the curvature in the results. Engines are known to have nonlinear characteristics over the operating range. Exhaust emissions are probably also nonlinear in this range.

6. Two or three levels of engine RPM. As discussed in 5, it is preferable to let the dynamometer control the RPM while adjusting the torque by varying the amount of fuel. The comments above about curvature apply to RPM as well.

7. Two or three levels of compression ratio spanning the normal range of this factor for the engine type.

8. Two or three levels of injection timing (spark timing) spanning the operating range for the engine type.

Note: A full two level factorial design with 8 variables requires 256 test runs. With 3 levels each, 6561 runs are needed. With 2 flow restriction levels, 4 fuels, 3 levels of torque, 3 levels of RPM, 2 compression ratios, and 2 timing settings, 288 test runs are needed. This number can be reduced significantly, to 20 - 64 tests, in a screening experiment. The screening experiment might show certain of the independent variables to have no effect so they could be dropped in later testing.

APPENDIX B

U.S. Coast Guard/U.S. Maritime Administration
Cooperative Research on Marine Engine Exhaust Emissions

TEST PROTOCOL FOR

SHIPBOARD MAIN PROPULSION DIESEL ENGINE EMISSIONS TESTS

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Prepared for:

U.S. DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD
Office of Engineering, Logistics, and Development
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and

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TABLE OF CONTENTS

SECTION 1 - General

1.1 Proposed Tests

This protocol describes tests to be performed on U.S. Coast Guard cutters to determine the exhaust emissions from the cutters' main propulsion diesel engines. A series of steady state tests will be conducted at five operating points along each cutter's propeller torque/SRPM curve. The five operating points will be chosen to represent frequent operating conditions. Additional tests will be conducted by accelerating the cutter from dead stop to full speed ahead at the maximum safe throttle setting and similarly from dead stop to full astern. The cutters will also be tested by bringing the throttles to all stop with the cutter travelling full speed ahead. These comprise the basic tests. Optional testing may be performed at several speeds in shallow water or while towing.

Various engine operating characteristics will be measured during the tests. These include fuel consumption, shaft RPM (SRPM), and shaft torque. The resulting characteristics of the engine exhaust will be measured. These include component gases, exhaust temperature, and exhaust back pressure. In general, the procedures of ISO 8178 series will be followed to the extent practical.

1.2 Test Objectives

The primary objective of these tests is to determine if Coast Guard cutters can meet the standards of the Clean Air Act as Amended in 1990 (CAAA90). A single emission value for each pollutant of interest - CO, NO_x, SO_2 - will be calculated as a weighted average of the calculated mean values at each of the five test operating points. The sum of the pollutants from all propulsion engines will be used. The weights will be determined prior to the tests based on the percentage of the time the cutter operates in the vicinity of the operating point. The percentages for the five operating points must add to 100 percent.

The information obtained from the acceleration and deceleration tests will not be used in the emissions calculations but will provide guidance on how engine emission performance might be improved. The optional shallow water and towing tests provide information about engine pollutants when the engines are under higher than normal load conditions.

1.3 References

a. ISO/DP 8178-1 RIC Engines - Exhaust Emission Measurement; Part 1: Test Bed Measurement of Gaseous and Particulate Exhaust Emissions from RIC Engines.

b. ISO/CD 8178-2 RIC Engines - Exhaust Emission Measurement; Part 2: At Site Measurement of Gaseous and Particulate Exhaust Emissions from RIC Engines. - Special requirements for using ISO 8178-1 at site.

c. ISO 8178-4 RIC Engines - Exhaust Emission Measurement; Part 4: Test Cycles for Different Engine Applications.

1.4 Location, Time, and Duration of Tests

Location - To be determined.

Time - To be determined.

Duration of Tests - 2 to 3 days plus installation of instrumentation.

Number of Times Tests Must be Run - Varies with each test type. See Section 2.

1.5 Test Prerequisites

Crew Training - The only crew training required is training in the normal operation of the cutter.

Prior Tests Required - None.

Facilities and Resources Required - The cutter must be available for testing for at least one week. This includes time for installation of test equipment as well as the tests themselves. Larger cutters with more complex propulsion plants will require more time to instrument.

Personnel Required - Two to three test personnel are required to collect data and tend the test equipment on smaller cutters. Larger cutters will require more test personnel.

Test Equipment, Applied Instrumentation, and Data Recording Equipment - The following generic test equipment is required. The exact equipment used may vary depending on the cutter type. Equipment accuracy requirements are specified in reference (b) section 7.3.

- Shaft RPM transducers and recording equipment for all shafts
- Shaft Torque transducers and recording equipment for all shafts (If the engines are not directly coupled to the propeller shafts, the above two measurements must be made on the shafts of the engines as well as on the propeller shafts)
- Fuel flow meters for measuring the fuel into and out of each engine.
- Thermometer for measuring the air temperature in the vicinity of the engine intakes
- Barometer for measuring the air pressure in the vicinity of the engine intakes
- An instrument for measuring the humidity of the air near the engine intakes
- An instrument or instruments and associated recording equipment for determining exhaust gas concentrations of CO, CO_2, NO, NO_2, SO_2, O_2, and total hydrocarbons. The sampling lines for this equipment must be heated per the standards prescribed in reference (a) or be otherwise suitable for sampling hot exhaust gases containing water vapor.
- A thermometer for measuring and recording the exhaust gas temperature at the location of the sampling probe.
- A pressure transducer for measuring and recording the exhaust gas back pressure at the location of the sampling probe.
- A transducer for measuring turbocharger speed (If engine has turbochargers)

Additional data may be obtained from the installed cutter instrumentation provided the equipment is maintained to the Coast Guard's calibration standards. These data include: wind speed and direction, water depth, engine coolant inlet and outlet temperatures, and lubricating oil temperature(s).

Logistics Equipment Requirements (Spare Test Hardware) - The planned test period is 2 - 3 days. Spares for critical test instruments are to be provided as considered necessary for tests of this duration.

1.6 Methods of Measurement - The general methods of measurement for these tests are specified in references (a) thru (c). These references should be consulted for information beyond that given in the discussion below. Each test measurement is listed below with a recommended measurement method. Alternate measurement methods are acceptable if the accuracy of the measurements can be maintained within the requirements of ISO 8178 series.

Shaft RPM - Any standard RPM measuring transducer can be used provided it meets the accuracy requirements of reference (b). These data shall be continuously recorded during each test cycle.

Shaft Torque - Any standard Torque measuring transducer can be used if it meets the accuracy requirements of reference (b). These data shall be continuously recorded during each test cycle.

Fuel Consumption - The measurement of fuel consumption is one of the most critical for these tests. Fuel consumption is also difficult to measure because part of the fuel entering the engine is often used to cool the injectors and is returned to the fuel tank. Therefore, both the fuel entering the engine and leaving the engine must be measured and the difference between the two must be within 3 percent of the actual fuel used. The fuel use rate is used to calculate the exhaust flow rate so the fuel flow must be measured as accurately as possible. Continuous recording of fuel flow rates is preferred but not essential.

Air Pressure at Intake - A barometer shall be used to measure air pressure in the vicinity of, but not immediately adjacent to, the intake.

Air Temperature at Intake - A thermometer shall be used to measure air temperature in the vicinity of, but not immediately adjacent to, the intake. The dry bulb temperature of a psychrometer may be used.

Absolute Air Humidity at Intake - A wet/dry thermometer (psychrometer) may be used or a direct reading humidity meter of sufficient accuracy.

Percent Oxygen in the Air - The percent of oxygen in the intake air shall be measured and recorded using an oxygen meter at the beginning and end of testing and at any time there is reason to believe that the percent oxygen might have changed.

Turbocharger Speed - The easiest way to measure turbocharger speed is to record the vibration signature of the turbocharger on the external casing. The vibration frequency at the primary peak can be used to determine turbocharger RPM with sufficient accuracy.

Air Pressure after Charge Air Cooler - This is an optional measurement that should only be recorded if a pressure gage is provided on the engine.

Air Temperature after Charge Air Cooler - This is an optional measurement that should only be recorded if a temperature gage is provided on the engine.

Fuel Rack Position - Fuel rack position shall be read from the installed engine scale. Each cylinder shall be recorded if separate rack position scales are provided.

Coolant Inlet Temperature - The temperature of the primary engine coolant (generally fresh water) entering the engine shall be recorded from the installed temperature gages. The cooling water temperature should not vary significantly after the engine is warmed up. However, the cutter's Engineering Log should be consulted to check for variations that occurred during testing. These comments also apply to the coolant outlet temperature.

Coolant Outlet Temperature - The temperature of the primary engine coolant leaving the engine shall be recorded from the installed temperature gages.

Lubricating Oil Temperature (Inlet Temperature) - If the lubricating oil system uses external cooling, the inlet temperature of the oil into the engine shall be recorded from the installed temperature gages. If there is no external cooling or if the engine has a single oil temperature gage, this temperature shall be recorded. The oil temperature should not vary significantly after the engine is warmed up. However, the cutter's Engineering Log should be consulted to check for variations that occurred during testing. These comments also apply to oil outlet temperature.

Lubricating Oil Outlet Temperature - Outlet oil temperature from the engine shall be recorded from installed temperature gages when external cooling is used.

Lubricating Oil Specifications or Sample - Record engine lubricating oil type as provided by cutter's crew. Notes shall be taken on the type and frequency of lubricating oil treatment used on the cutter and the time since the last oil treatment or oil change. If there is uncertainty about the type or quality of the oil in the engine, a sample shall be taken for further testing. The test results shall be included in the test report.

Type of Fuel Used - Record fuel type as provided by cutter's crew.

Fuel Oil Sample - A sample of the fuel used during the tests shall be drawn from the fuel line to the engines or, if that is not possible, from the fuel tank used during the tests. A sufficient sample, one liter, shall be drawn to permit analysis of the fuel's properties and constituents. The test results shall be included in the test report.

Draft Readings Fore and Aft - Draft readings shall be recorded at the beginning and end of each day of testing.

Relative Wind Speed and Direction - Record data from cutter's anemometer at least hourly during testing.

Significant Wave Height and Direction - Record visual observations provided by experienced ship's crewman or test personnel periodically during testing, particularly whenever a significant change in sea conditions is noted.

Date of Last Drydocking or Bottom Cleaning - Record data provided by cutter's crew.

Engine Injector Size and Timing - Record data for each engine provided by cutter's crew. Measurements may be necessary if uncertainty exists.

Engine Make and Model Number - Record data from each engine nameplate.

Engine Serial Number - Record data from each engine nameplate.

Reduction Gear Make and Model Number - Record data from each reduction gear nameplate.

Reduction Gear Reduction Ratio Ahead and Astern - Record data from each reduction gear nameplate.

Propeller Type (Number of Blades, Diameter, Pitch, Developed Area Ratio) - This information may be obtained from shipboard personnel or from the Naval Engineering Division at C.G. Headquarters. Propeller type shall be included in the test report.

Water Depth - Installed cutter fathometer may be used. Record depth and time of any significant depth changes during testing. Exact depth isn't critical to test results.

Exhaust Gases - The methods for measuring exhaust gas concentrations are discussed in reference (a) section 15. These should be followed closely to ensure that measurements are in accordance with international standards.

Exhaust Back Pressure - Exhaust back pressure shall be measured each time exhaust gas samples are taken during steady state operations. The transducer used must measure only the static pressure in the exhaust line and must be installed as close as possible to the location of the exhaust gas sampling probe.

An acceptable alternate method for determining exhaust back pressure is to conduct a separate set of test runs. These runs could be conducted in rapid succession since back pressure should stabilize rapidly. At least two repetitions of the 5 operating points should be tested with the runs made in random order. The mean exhaust back pressure versus SRPM can then be plotted for use with all steady state test runs.

Exhaust Temperature - Exhaust temperature shall be measured each time exhaust gas samples are taken during steady state operations. The transducer used shall be installed as close as possible to the location of the exhaust gas sampling probe.

1.7 Hardware Configuration - Only those changes to the cutter's configuration that are essential to install test instrumentation will be made.

1.8 Data Sheets - A single set of data sheets is attached which can be used for all tests described in this protocol.

1.9 Pre-operational Checklist - The following items should be checked before leaving for the operating area.

- Essential cutter equipment is operational
- Drafts fore and aft are recorded
- Depth at proposed operating area is satisfactory
- Sea conditions in operating area are acceptable
- All test instrumentation is installed and operational
- Sufficient recording media are on board
- Test personnel know their assigned jobs during testing
- Cutter's crew has been briefed on tests to be performed

1.10 Concurrent Testing - No concurrent testing is planned.

1.11 Approvals, Authorities, and Responsibilities - The cutter's operational commander is responsible for designating a time when the cutter is available for testing. During testing, the cutter will be operated by its normal crew. Test instrumentation will be installed by R&D Center personnel with some assistance from the crew. Data recording is the responsibility of the R&D Center test personnel. They may request assistance from the cutter's crew for individual items of data.

1.12 Test Report - At the completion of testing, a test report shall be prepared which documents the test results. This report shall be in the format of DOT Order 1700.18B, "Acquisition, Publication and Dissemination of DOT Scientific and Technical Reports." Data shall be presented in metric units with U.S. Standard units in parentheses after the metric units.

SECTION 2 - Specific Tests

2.1 Free Running Tests

2.1.1 Test Description - The free running tests are intended to be steady state tests in calm, deep water. Deviation from this ideal may be necessary to expedite testing but conditions as close to the ideal as possible should be sought. "Deep water" is a term which depends on the cutter's maximum cross-sectional area and maximum speed. The following two formulas give the minimum water depths for negligible wave making and residual resistance, respectively. The higher depth should be used. Note, "g" is the acceleration of gravity.

$$Depth \geq \frac{(Maximum\ Speed)^2}{0.16 \times g}$$

$$Depth \geq 10 \times \sqrt{Cross\text{-}sectional\ Area}$$

However, the effects on speed and resistance will be less than 2 percent if the following limits are used:

$$Depth \geq \frac{(Maximum\ Speed)^2}{0.36 \times g}$$

$$Depth \geq 4 \times \sqrt{Cross\text{-}sectional\ Area}$$

The tests should be conducted with a minimum of wind and little wave action. The conditions may be considered "calm" if significant wave height is below 0.6 meters (2 feet) and wind speed is below 15 knots. When possible, the tests should be run with the seas on the cutter's beam, particularly in higher wave conditions. All runs must be made in the same relative direction to the wind and waves. If tests must be conducted in water that is shallower than required, all tests shall be conducted in water of the same depth.

All tests will be conducted with all shafts (on multishaft cutters) turning at the same SRPM. When multiple engines can be assigned to a shaft, as in the case with some diesel electric plants or when more than one diesel shares a reduction gear, only those engines that would normally be needed at the test speed should be operating. Higher speeds may require more diesels on line. Only diesel engines are being tested. Full speed for these tests is the maximum speed on diesels only.

Tests shall be conducted at 5 speeds (operating points) including idle ahead, full speed ahead, and 3 intermediate speeds. The intermediate speeds used shall be selected in advance. Speeds should be chosen which represent frequent operating points such as "cruising speed" or "patrol speed." Weighting factors, totalling to 1.0, shall be chosen for the 5 speeds based on the percentage of time the cutter operates at or near the speed chosen. These weights will determine the single number estimate of cutter exhaust emissions. Tests at each of the 5 operating points shall be repeated 4 times when possible to obtain a better estimate of the average amount of emissions at each of the operating points. Five test runs, one at each operating point, constitute a block of runs. Data will be collected by repeating the block of runs 4 times. Within each of these 4 blocks of runs the order of the 5 runs will be randomized so that each block has a different run order. This procedure helps to ensure that external factors, which aren't being measured, will have minimal effect on the results.

On multiengined cutters, there will be a set of 4 data points for each engine at each operating point. The RPM for each mechanically coupled diesel will be the same if the SRPM on all shafts is the same (within ± 2 %). The torque produced by the engines may differ. The torque differences will likely cause the engines to have different emission levels. If engines are not mechanically coupled to the shafts, as is the case with diesel-electric drives, the engine RPMs must be kept equal to one another and the same for all tests at the same operating point. If more than one engine powers a shaft, the load must be balanced between the engines.

The mean emission rate for each engine and each exhaust gas will be determined by averaging the 4 emission rates measured at each operating point. The confidence interval on the mean values will also be estimated from the data. The mean emission rates for each of the engines, at an operating point, will be summed to find the total emission rate for the cutter at that operating point. Finally, the weighting factors will be multiplied by the total emission rates and the results summed over the 5 operating points to determine the single number emission level for each pollutant.

2.1.2 Test Procedures - This section discusses the procedures for an individual test run. All test runs are identical except for the operating point.

The run cycle begins with acceleration or deceleration from the previous speed to the test speed for the current run. Once the engine has stabilized at the new test speed, a 10 minute steady state run interval begins.

During this interval the cutter should maintain a steady course and speed and limit rudder angle to less than 10 degrees. At the end of the 10 minutes, data on emissions will be collected. At the end of data collection, the cutter may proceed to the next speed in sequence.

Data recording for torque and RPM begins at the start of each run cycle and continues to the end. Since test runs are made one after another with no break between, data recording will be continuous for long periods. Breaks in testing may be made between runs to change recording media as necessary. A voice track on the recording tape should be used to record key points in the sequence of runs such as the speed change point, start of the steady state run, and the data collection interval at end of the steady state run. If multiple recording media are used, these key points shall be noted on all media. Periodic measurements shall be taken as discussed in section 2.1.4. The time of all measurements shall be logged along with the start and stop times for each speed run. A convenient run number should be assigned to each run for later reference.

2.1.3 Test Schedule - Table 1 gives 40 random orders for test runs out of the possible 120 combinations. Other random orders may be used. To use Table 1, four column numbers should be chosen blindly and the run orders for the chosen columns used for testing. The numbers in Table 1 designate operating points from the lowest (1) to the highest (5).

Table I - Random Run Orders

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	3	3	4	5	2	4	2	2	5	3	4	4	4	1	4	5	5	3	4
3	4	2	3	4	3	5	3	3	3	5	3	3	5	2	2	4	2	5	1
4	2	5	5	2	4	1	1	1	2	1	2	2	1	4	3	3	4	4	5
1	5	4	1	3	5	3	4	5	4	4	1	5	2	5	5	2	3	2	3
5	1	1	2	1	1	2	5	4	1	2	5	1	3	3	1	1	1	1	2

21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
2	3	1	1	2	1	2	1	2	4	2	5	2	5	2	5	3	3	2	1
4	5	4	2	4	2	5	4	1	3	4	2	1	1	1	3	4	4	3	2
3	4	2	3	3	5	4	5	4	1	5	3	3	3	4	4	5	2	5	4
5	1	5	4	1	4	1	3	5	2	3	1	4	2	3	2	1	1	4	3
1	2	3	5	5	3	3	2	3	5	1	4	5	4	5	1	2	5	1	5

Tests shall be conducted in block order. That is, a block must be completed before proceeding to runs in the next block. This ensures that a maximum of usable data is available should testing end early.

All twenty test runs (4 blocks of 5) should be made on the same day in as nearly identical conditions as possible. Each run is estimated to take 15 - 20 minutes. The twenty runs should take 5 - 6 hours to complete. If the runs span more than one day, the break point should be between blocks of runs, not within a block. A lunch break should also be taken between blocks when possible.

2.1.4 Data to be Recorded

Shaft RPM - These data shall be continuously recorded during the test cycle. This is the primary independent variable for these tests. All SRPMs must remain within ± 2 percent of the nominal SRPM chosen for the operating point. Engine speed is proportional to shaft speed for mechanically coupled engines. Engine speeds which are within ± 2 percent of the nominal engine speed may be combined as one data set. If one or more engines is outside this limit, which is unlikely given the precision of governors used on diesel engines, the engine(s) shall be considered to be at a different operating point and the resulting data can not be combined to form a single data set.

Engine RPM - If engines are not mechanically coupled to the shafts, engine RPM for each engine shall be recorded continuously.

Shaft Torque - These data shall be continuously recorded during the test cycle.

Engine Torque - If engines are not mechanically coupled to the shafts, engine torque shall be recorded continuously for each engine.

Fuel Consumption - Continuous recording of fuel flow rates is preferred and should be made over the test cycle. If manual reading of fuel flow is necessary, these data shall be recorded during the last 3 minutes of the 10 minute steady state interval.

Air Pressure at Intake, Air Temperature at Intake, and Absolute Air Humidity at Intake - Record periodically, at least hourly, at any convenient time during testing.

Percent Oxygen in the Air - The percent of oxygen in the intake air shall be measured and recorded at the beginning and end of the day's testing and at any time there is reason to believe that the percent oxygen might have changed.

Turbocharger Speed - Turbocharger speed shall be measured during the last 3 minutes of the 10 minute steady state interval.

Air Pressure after Charge Air Cooler - Read and record during the last 5 minutes of the steady state interval if available.

Air Temperature after Charge Air Cooler - Read and record during the last 5 minutes of the steady state interval if available.

Fuel Rack Position - Read and record during the last 3 minutes of the steady state interval.

Coolant Inlet Temperature, Coolant Outlet Temperature, Lubricating Oil Temperature (Inlet Temperature), and Lubricating Oil Outlet Temperature - Read and record these temperatures after the engines are up to operating temperature. Data from the cutter's Engineering Log may be copied to show hourly changes occurring during the day's testing.

Draft Readings Fore and Aft - Draft readings shall be recorded at the beginning and end of each day of testing.

Relative Wind Speed and Direction - Record data from cutter's anemometer at least hourly during testing.

Significant Wave Height and Direction - Record visual observations provided by experienced ship's crewman or test personnel periodically during testing, particularly whenever a significant change in sea conditions is noted.

Water Depth - An average depth in the test area may be recorded if all testing is in deep water. In shallower water, the depth shall be recorded at a frequency deemed adequate to account for depth variations. This could vary from continuous recording where the depth changes frequently to hourly recording if depth changes are gradual.

Exhaust Gases - Exhaust gas concentrations of CO, CO_2, NO, NO_2, SO_2, O_2, and total hydrocarbons shall be determined at the end of the 10 minute steady state interval.

Exhaust Back Pressure - The exhaust back pressure shall be read and recorded during the last 5 minutes of the steady state interval or concurrent with the exhaust gas concentration measurements.

Exhaust Temperature - The exhaust temperature shall be read and recorded during the last 5 minutes of the steady state interval or concurrent with the exhaust gas concentration measurements.

2.1.5 Data Analysis - The following description is based on taking four sets of data on two propulsion diesels. This is most common arrangement on cutters. The analysis needs to be changed only slightly for other arrangements.

During the tests, measurements are made of the concentration of exhaust gas components in the exhaust. In order to calculate the total amount of emissions, the exhaust mass flow must be determined. The method detailed in Appendix A.1 of reference (a) shall be used. This is a carbon balance method based on the flow rate of fuel, the components in the fuel, and the measured exhaust gas concentrations. This analysis must be performed on each engine for each test run. The resulting emissions in grams/hour are computed from the emission concentrations (ppm) and the exhaust mass flow rate (kg/h). The emissions in grams/hour are used in all further calculations.

One or more plots shall be prepared with SRPM as the X-axis and shaft torque (Nm), fuel consumption (kg/h), and emission rates of CO, NO, NO_2, SO_2, and O_2 (g/h) as the Y-axes. These plots shall show the mean value of each dependent variables (8 degrees of freedom) and the 95 percent confidence interval for each mean value (7 degrees of freedom). Separate plots shall be prepared showing the same emissions data plotted against fuel consumption on the X-axis and against shaft power (kW) on the X-axis. The mean values for each of the five operating points shall be determined from this analysis.

The test procedure should eliminate any wide variations in the data. However, if one or more data points are clearly inconsistent with the other data points they should be investigated further. If it is unlikely that the data points could come from the same population as the other data (in a statistical sense) the outlying data should be eliminated from the analysis.

The single emission number for each pollutant is calculated by the following formula:

$$Emission\ Number = \sum_{Op.\ Points} (Weighting\ Factor * \sum_{Engines} Mean\ Value)$$

All other values measured during these tests shall be summarized in tables included in the appendices of the test report. These variables are expected to be useful for further analysis of the data and perhaps will help in determining a cause and effect relationship between engine parameters and the resulting emissions. This information will also help to correlate the test results from CFR engine tests with the ship test data.

2.1.6 Expected Results - Smoothly varying curves of emission rates versus SRPM are expected. The curves may increase or decrease with speed or have peaks or valleys. Shaft power, fuel consumption, and exhaust mass flow should increase smoothly with speed.

2.2 Ahead and Astern Acceleration Tests

2.2.1 Test Description - The ahead and astern acceleration tests are intended to measure the exhaust emission concentrations under the highest practical engine loading conditions. These are transient tests with the cutter accelerating from dead stop to full speed ahead or astern in the shortest safe time. Full speed in these cases is defined as the maximum speed the cutter's captain is willing to go. Because high engine loading is desired, these tests should be conducted in shallow water if possible. This is not critical to the test results. Satisfactory data can be collected even in deep water. The on-scene test director should chose a local test site that allows the top speed to be reached and has a depth that permits safe operations. A safety margin must be allowed on depth because the ship will squat during acceleration and will temporarily have a deeper draft than measured at the pier.

Wind and wave action will have little effect on these tests. However, if significant waves are present, the tests should be run with the seas on the cutter's beam.

Tests shall be conducted with all shafts and the number of on-line diesels needed at full speed. The throttles are to be advanced rapidly from stop to full ahead or astern. The cutter's captain may place restrictions on how rapidly this may be done and the top speed. An attempt shall be made to duplicate the throttle advance rate for all similar tests. The faster the throttle is advanced, the better for test purposes. The goal is to force the engine governors to use their torque limiting features. Thus, the maximum amount of fuel will be injected into the engine for a given speed. This will likely cause the worst pollution.

Only emissions' concentrations (ppm) will be measured in these tests, not emission rates (g/h). The exhaust flow rate is difficult to measure because of the rapidly changing conditions during acceleration and can not be accurately correlated with the emissions' concentrations. The concentrations will be compared, along with the SRPM and power, to the values determined during the free running tests. This should provide insight into some of the factors that affect the concentration of emissions.

2.2.2 Test Procedures - In section 2.3, deceleration tests are discussed. The acceleration tests and the deceleration tests should be combined as one sequence of tests. Sections 2.2.3 and 2.3.3 both give the recommended sequence.

The test procedure is a simple one. With the cutter dead in the water and engines idling, the throttles are advanced to full as rapidly as can be done safely. This may involve clutching in the diesels. No attempt to equalize the SRPM between shafts is necessary but both throttles should be advanced together. Emissions, shaft (engine) torque, and SRPM (engine RPM) are measured continuously during the acceleration to full speed. Once the cutter reaches full speed, a short (3 - 5 minute) steady state period shall be allowed for the engines to stabilize before conducting a deceleration test. Cutter specific considerations, such as water entering the exhaust, may require a reduction in the steady state interval. However, the engines should at least be allowed to reach steady state conditions at the top speed before beginning a deceleration test. The test cycle is repeated at least 3 times to collect confirming data.

2.2.3 Test Schedule - The following test schedule applies for all acceleration and deceleration tests.

The sequence of runs begins with the cutter on scene at the test site, dead in the water, and with all necessary engines warmed up and idling. After each acceleration or deceleration, a brief period shall be allowed for the engines to stabilize at idle or full speed. The following sequence of tests is recommended.

Ahead Acceleration
Deceleration
Astern Acceleration
Deceleration
Astern Acceleration
Deceleration
Ahead Acceleration
Deceleration
Ahead Acceleration
Deceleration
Astern Acceleration
Deceleration

Each acceleration and subsequent steady state run is expected to take about 10 minutes. Decelerations may take 10 - 15 minutes each. The entire sequence of tests should take no more than 3 hours.

2.2.4 Data to be Recorded

Shaft RPM - These data shall be continuously recorded during the test cycle.

Engine RPM - If engines are not mechanically coupled to the shafts, engine RPM for each engine shall be recorded continuously.

Shaft Torque - These data shall be continuously recorded during the test cycle.

Engine Torque - If engines are not mechanically coupled to the shafts, engine torque shall be record continuously for each engine.

Fuel Consumption - If continuous recording of fuel flow rates is available, fuel flow shall be recorded continuously for each engine. Otherwise, fuel consumption need not be recorded.

Air Pressure at Intake, Air Temperature at Intake, and Absolute Air Humidity at Intake - Record periodically, at least hourly, at any convenient time during testing.

Percent Oxygen in the Air - The percent of oxygen in the intake air shall be measured and recorded at the beginning and end of the day's testing and at any time there is reason to believe that the percent oxygen might have changed.

Turbocharger Speed - Turbocharger speed need not be measured but will provide useful data if continuous recording is available.

Coolant Inlet Temperature, Coolant Outlet Temperature, Lubricating Oil Temperature (Inlet Temperature), and Lubricating Oil Outlet Temperature - Read and record these temperatures after the engines are up to operating temperature. Data from the cutter's Engineering Log may be copied to show hourly changes occurring during the day's testing.

Draft Readings Fore and Aft - Draft readings shall be recorded at the beginning and end of each day of testing.

Relative Wind Speed and Direction - Record data from cutter's anemometer at least hourly during testing.

Significant Wave Height and Direction - Record visual observations provided by experienced ship's crewman or test personnel periodically during testing, particularly whenever a significant change in sea conditions is noted.

Water Depth - An average depth in the test area shall be recorded.

Exhaust Gases - Exhaust gas concentrations of CO, NO, NO_2, SO_2, and O_2 shall be measured continuously during each test run.

2.2.5 Data Analysis - Separate plots shall be prepared for each exhaust gas and acceleration direction. These plots shall show the exhaust gas concentration (percent or ppm) and shaft power (kW) plotted against SRPM. The mean value curve of steady state concentration and power shall be shown on each plot. Dual vertical scales shall be used with the left scale showing exhaust gas concentration and the right scale showing power. Each plot will have 6 curves for exhaust gas concentration plus the steady state mean curve as well as 7 power curves. Different line types shall be used to differentiate the curves. A legend shall be include to designate the different line types. No other data analysis is required.

2.2.6 Expected Results - Shaft torque will increase rapidly to the limit set by the governors and then approach steady state full power torque as the cutter's speed increases. Exhaust gas concentrations should logically follow a similar pattern but may have a different response.

2.3 Deceleration Tests

2.3.1 Test Description - The ahead and astern deceleration tests are intended to measure the exhaust emission concentrations under the lowest practical engine loading conditions. These are transient tests with the cutter decelerating from full speed ahead or astern to dead stop. Wind and wave action will have little effect on these tests. However, if significant waves are present, the tests should be run with the seas on the cutter's beam.

Tests shall be conducted with all shafts and the number of on-line diesels needed at full speed. The throttles are to be moved rapidly from full ahead or astern to stop. Shaft rotation is not to be reversed to decrease speed more rapidly. An attempt shall be made to duplicate the throttle rate for all similar tests. The faster the throttle is moved, the better for test purposes. The goal is to force the engine governors to decrease fuel rapidly while the engines are still at high RPM. The effect this will have on emissions is not known.

Only emissions' concentrations (ppm) will be measured in these tests, not emission rates (g/h). The exhaust flow rate is difficult to measure because of the rapidly changing conditions during deceleration and can not be accurately correlated with the emissions' concentrations. The concentrations will be compared, along with the SRPM and power, to the values determined during the free running tests. This should provide insight into some of the factors that affect the concentration of emissions.

2.3.2 Test Procedures - The acceleration tests discussed in the previous section and the deceleration tests should be combined as one sequence of tests. Sections 2.2.3 and 2.3.3 both give the recommended sequence.

With the cutter moving at full speed ahead or astern, the throttles are returned to all stop rapidly. No attempt to equalize the SRPM between shafts is necessary but both throttles should be moved together. Emissions, shaft (engine) torque, and SRPM (engine RPM) are measured continuously during the deceleration to stop. Once the cutter stops, a short (3 - 5 minute) time shall be allowed for the engines to stabilize at idle before conducting the next test. The test cycle is repeated at least 3 times to collect confirming data.

2.3.3 Test Schedule - The following test schedule applies for all acceleration and deceleration tests.

The sequence of runs begins with the cutter on scene at the test site, dead in the water, and with all necessary engines warmed up and idling. After each acceleration or deceleration, a brief period shall be allowed for the engines to stabilize at idle or full speed. The following sequence of tests is recommended.

Ahead Acceleration
Deceleration
Astern Acceleration
Deceleration
Astern Acceleration
Deceleration
Ahead Acceleration
Deceleration
Ahead Acceleration
Deceleration
Astern Acceleration
Deceleration

Each acceleration and subsequent steady state run is expected to take about 10 minutes. Decelerations may take 10 - 15 minutes each. The entire sequence of tests should take no more than 3 hours.

2.3.4 Data to be Recorded - The listing below is the same as for acceleration tests.

Shaft RPM - These data shall be continuously recorded during the test cycle.

Engine RPM - If engines are not mechanically coupled to the shafts, engine RPM for each engine shall be recorded continuously.

Shaft Torque - These data shall be continuously recorded during the test cycle.

Engine Torque - If engines are not mechanically coupled to the shafts, engine torque shall be record continuously for each engine.

Fuel Consumption - If continuous recording of fuel flow rates is available, fuel flow shall be recorded continuously for each engine. Otherwise, fuel consumption need not be recorded.

Air Pressure at Intake, Air Temperature at Intake, and Absolute Air Humidity at Intake - Record periodically, at least hourly, at any convenient time during testing.

Percent Oxygen in the Air - The percent of oxygen in the intake air shall be measured and recorded at the beginning and end of the day's testing and at any time there is reason to believe that the percent oxygen might have changed.

Turbocharger Speed - Turbocharger speed need not be measured but will provide useful data if continuous recording is available.

Coolant Inlet Temperature, Coolant Outlet Temperature, Lubricating Oil Temperature (Inlet Temperature), and Lubricating Oil Outlet Temperature - Read and record these temperatures after the engines are up to operating temperature. Data from the cutter's Engineering Log may be copied to show hourly changes occurring during the day's testing.

Draft Readings Fore and Aft - Draft readings shall be recorded at the beginning and end of each day of testing.

Relative Wind Speed and Direction - Record data from cutter's anemometer at least hourly during testing.

Significant Wave Height and Direction - Record visual observations provided by experienced ship's crewman or test personnel periodically during testing, particularly whenever a significant change in sea conditions is noted.

Water Depth - An average depth in the test area shall be recorded.

Exhaust Gases - Exhaust gas concentrations of CO, NO, NO_2, SO_2, and O_2 shall be measured continuously during each test run.

2.3.5 Data Analysis - Separate plots shall be prepared for each exhaust gas and deceleration direction. These plots shall show the exhaust gas concentration (percent or ppm) and shaft power (kW) plotted against SRPM. The mean value curve of steady state concentration and power shall be shown on each plot. Dual vertical scales shall be used with the left scale showing exhaust gas concentration and the right scale showing power. Each plot will have 6 curves for exhaust gas concentration plus the steady state mean curve as well as 7 power curves. Different line types shall be used to differentiate the curves. A legend shall be include to designate the different line types. No other data analysis is required.

2.3.6 Expected Results - Shaft torque will decrease rapidly (it may go negative) and then approach steady state idle torque as the cutter's speed decreases. Exhaust gas concentrations should logically follow a similar pattern but may have a different response.

2.4 Towing or Shallow Water Tests

2.4.1 Test Description - Towing and shallow water tests are identical in concept to the free running tests. The only difference is the engine loading. Towing and shallow water operations require more shaft torque for the same SRPM when compared to free running conditions. This will likely affect the emissions from the engines.

Towing tests should be conducted with a tow which adds a significant load to the engines, such as a vessel of similar size to the cutter. Shallow water tests should be conducted in the least water depth available that permits safe operation of the cutter. All shallow water tests should be conducted in water of the same depth. Water depth should vary no more than ± 10 percent from the mean test depth. There is usually no dramatic loading effects due to water depth until the water depth is below 3 times the still water draft. The best range of depths to run shallow water tests is 1.5 - 3 times the cutter's draft.

Tests may be conducted at 1 - 5 speeds (operating points) including idle ahead, full speed ahead (corrected for operating conditions), and intermediate speeds. If local conditions restrict the speeds that can be run, the maximum speed may be reduced and the number of speeds tested may be reduced to 4 or 3 (with loss of data). Tests at each of the operating points shall be repeated at least 2 times to obtain a better estimate of the average amount of emissions at each of the operating points. A block of test runs is made up of one run at each operating point. Data will be collected by repeating the block of runs 2 or more times. Within each of these blocks of runs the order of the runs will be randomized so that each block has a different run order. This procedure helps to ensure that external factors, which aren't being measured, will have minimal effect on the results.

On multiengined cutters, measurements on each engine will be combined into a common data set. The RPM for mechanically coupled diesels will be the same if the SRPM on both shafts is the same. The torque produced by the engines may differ. This is considered to be within the normal variability of shipboard installations. As long as the RPMs of the engines are the same, the resulting emissions can be combined into one set of data at each operating point. The resulting mean emission value will apply to all engines on the cutter. If engines are not mechanically coupled to the shafts, as is the case with diesel-electric drives, the engine RPMs must be kept equal to one another and the same for all tests at the same operating point. If more than one engine powers a shaft, the load must be balanced between the engines.

The test results for each of the dependent variables of interest will be averaged at each of the operating points to determine a mean value. The confidence interval on this mean value will also be estimated from the data. It is not necessary to estimate a single number emission value from these data.

2.4.2 Test Procedures - This section discusses the procedures for an individual test run. All test runs are identical except for the operating point.

The run cycle begins with acceleration or deceleration from the previous speed to the test speed for the current run. Once the engine has stabilized at the new test speed, a 10 minute steady state run interval begins. During this interval the cutter should maintain a steady course and speed and limit rudder angle to less than 10 degrees. At the end of the 10 minutes, data on emissions will be collected. At the end of data collection, the cutter may proceed to the next speed in sequence.

Data recording for torque and RPM begins at the start of each run cycle and continues to the end. Since test runs are made one after another with no break between, data recording will be continuous for long periods. Breaks in testing may be made between runs to change recording media as necessary. A voice track on the recording tape should be used to record key points in the sequence of runs such as the speed change point, start of the steady state run, and the data collection interval at end of the steady state run. If multiple recording media are used, these key points shall be noted on all media. Periodic measurements shall be taken as discussed in section 2.4.4. The time of all measurements shall be logged along with the start and stop times for each speed run. A convenient run number should be assigned to each run for later reference.

2.4.3 Test Schedule - Table 1 in section 2.1.3 provides randomization sequences for runs within a block. If fewer than 5 operating points make up a block, the order of runs must still be randomized.

Tests shall be conducted in block order. That is, a block must be completed before proceeding to runs in the next block. This ensures that a maximum of usable data is available should testing end early.

All test runs should be made on the same day in as nearly identical conditions as possible. Each run is estimated to take 15 - 20 minutes. Ten runs should take 2-1/2 - 3 hours to complete. If the runs span more than one day, the break point should be between blocks of runs, not within a block. A lunch break should also be taken between blocks when possible.

2.4.4 Data to be Recorded - The following list of data is the same as given for free running tests.

<u>Shaft RPM</u> - These data shall be continuously recorded during the test cycle. This is the primary independent variable for these tests. All SRPMs must remain within 2 percent of the nominal SRPM chosen for the operating point. Engine speed is proportional to shaft speed for mechanically coupled engines. Engine speeds which are within ± 2 percent of the nominal engine speed may be combined as one data set. If one or more engines is outside this limit, which is unlikely given the precision of governors used on diesel engines, the engine(s) shall be considered to be at a different operating point and the resulting data can not be combined to form a single data set.

<u>Engine RPM</u> - If engines are not mechanically coupled to the shafts, engine RPM for each engine shall be recorded continuously.

<u>Shaft Torque</u> - These data shall be continuously recorded during the test cycle.

<u>Engine Torque</u> - If engines are not mechanically coupled to the shafts, engine torque shall be record continuously for each engine.

Fuel Consumption - Continuous recording of fuel flow rates is preferred and should be made over the test cycle. If manual reading of fuel flow is necessary, these data shall be recorded during the last 3 minutes of the 10 minute steady state interval.

Air Pressure at Intake, Air Temperature at Intake, and Absolute Air Humidity at Intake - Record periodically, at least hourly, at any convenient time during testing.

Percent Oxygen in the Air - The percent of oxygen in the intake air shall be measured and recorded at the beginning and end of the day's testing and at any time there is reason to believe that the percent oxygen might have changed.

Turbocharger Speed - Turbocharger speed shall be measured during the last 3 minutes of the 10 minute steady state interval.

Air Pressure after Charge Air Cooler - Read and record during the last 5 minutes of the steady state interval if available.

Air Temperature after Charge Air Cooler - Read and record during the last 5 minutes of the steady state interval if available.

Fuel Rack Position - Read and record during the last 3 minutes of the steady state interval.

Coolant Inlet Temperature, Coolant Outlet Temperature, Lubricating Oil Temperature (Inlet Temperature), and Lubricating Oil Outlet Temperature - Read and record these temperatures after the engines are up to operating temperature. Data from the cutter's Engineering Log may be copied to show hourly changes occurring during the day's testing.

Draft Readings Fore and Aft - Draft readings shall be recorded at the beginning and end of each day of testing.

Relative Wind Speed and Direction - Record data from cutter's anemometer at least hourly during testing.

Significant Wave Height and Direction - Record visual observations provided by experienced ship's crewman or test personnel periodically during testing, particularly whenever a significant change in sea conditions is noted.

Water Depth - An average depth in the test area may be recorded if all testing is in deep water. In shallower water, the depth shall be recorded at a frequency deemed adequate to account for depth variations. This could vary from continuous recording where the depth changes frequently to hourly recording if depth changes are gradual.

Exhaust Gases - Exhaust gas concentrations of CO, CO_2, NO, NO_2, SO_2, O_2, and total hydrocarbons shall be measured at the end of the 10 minute steady state interval.

Exhaust Back Pressure - The exhaust back pressure shall be read and recorded during the last 5 minutes of the steady state interval or concurrent with the exhaust gas concentration measurements.

Exhaust Temperature - The exhaust temperature shall be read and recorded during the last 5 minutes of the steady state interval or concurrent with the exhaust gas concentration measurements.

2.4.5 Data Analysis - The following description is based on taking two sets of data on two propulsion diesels. This is most common arrangement on cutters. The analysis needs to be changed only slightly for other arrangements.

During the tests, measurements are made of the concentration of exhaust gas components in the exhaust. In order to calculate the total amount of emissions, the exhaust mass flow must be determined. The method detailed

in Appendix A.1 of reference (a) shall be used. This is a carbon balance method based on the flow rate of fuel, the components in the fuel, and the measured exhaust gas concentrations. This analysis must be performed on each engine for each test run. The resulting emissions in grams/hour are computed from the emission concentrations (ppm) and the exhaust mass flow rate (kg/h). The emissions in grams/hour are used in all further calculations.

One or more plots shall be prepared with SRPM as the X-axis and shaft torque (Nm), fuel consumption (kg/h), and emission rates of CO, NO, NO_2, SO_2, and O_2 (g/h) as the Y-axes. These plots shall show the mean value of each dependent variables (4 degrees of freedom) and the 95 percent confidence interval for each mean value (3 degrees of freedom). Separate plots shall be prepared showing the same emissions data plotted against fuel consumption on the X-axis and against shaft power (kW) on the X-axis. The mean values for each of the operating points shall be determined from this analysis.

The test procedure should eliminate any wide variations in the data. However, if one or more data points are clearly inconsistent with the other data points they should be investigated further. If it is unlikely that the data points could come from the same population as the other data (in a statistical sense) the outlying data should be eliminated from the analysis.

All other values measured during these tests shall be summarized in tables included in the appendices of the test report. These variables are expected to be useful for further analysis of the data and perhaps will help in determining a cause and effect relationship between engine parameters and the resulting emissions. This information will also help to correlate the test results from CFR engine tests with the ship test data.

2.4.6 Expected Results - Smoothly varying curves of emission rates versus SRPM are expected. The curves may increase or decrease with speed or have peaks or valleys. Shaft power, fuel consumption, and exhaust mass flow should increase smoothly with speed and should be somewhat higher than similar measurements taken in the free running tests.

SECTION 3 - Data Sheets

The following pages contain a set of sample data sheets that can be used for all tests under this protocol. A separate set of data sheets must be used for each engine except for page 4. Only one page 4 is needed and it applies to the whole cutter. Individual tests above should be consulted to determine what data must be filled in.

EMISSIONS SHIP TEST DATA SHEET   Ship ____________   Class ________   Date __________

Description of Engine ____________________   Departure Drafts   Fwd ______   Return Drafts   Fwd ______

Percent O_2 Start ______   End ______   Aft ______   Aft ______

Note: Insert units used at bottom of header row for each column.   * Air temperature and pressure after a charge cooler (intercooler) if available.

Test No.	Fuel In/Out	Fuel Rack	CO conc.	CO_2 conc.	NO conc.	NO_2 conc.	SO_2 conc.	O_2 conc.	Turbo Speed	Exhaust Press.	Exhaust Temp.	Air * Press.	Air * Temp.

EMISSIONS SHIP TEST DATA SHEET Ship ____________ Class ________ Date __________

Description of Engine ______________________

Note: Insert units used at bottom of header row for each column. * Air temperature and pressure after a charge cooler (intercooler) if available.

Test No.	Fuel In/Out	Fuel Rack	CO conc.	CO_2 conc.	NO conc.	NO_2 conc.	SO_2 conc.	O_2 conc.	Turbo Speed	Exhaust Press.	Exhaust Temp.	Air * Press.	Air * Temp.

EMISSIONS SHIP TEST DATA SHEET Ship ______________ Class ________ Date __________

Description of Engine ______________________

Note: Insert units used at bottom of header row for each column. * Air values near engine intake.

	Air* Press.	Air* Temp.	Air* Humid.	Water Temp. In	Water Temp. Out	Oil Temp. In	Oil Temp. Out	Rel. Wind Speed	Rel. Wind Dir.	Sign. Wave Height	Rel. Wave Dir.	Water Depth
Reading												
Time												
Reading												
Time												
Reading												
Time												
Reading												
Time												
Reading												
Time												
Reading												
Time												
Reading												
Time												
Reading												
Time												

EMISSIONS SHIP TEST DATA SHEET Ship ________ Class ________ Date ________

Engine Location	Engine Make	Engine Model No.	Engine Serial No.	Injector Size	Injector Timing

Red Gear Location	Red. Gear Make	Red. Gear Model No.	Ahead Reduction Ratio	Astern Reduction Ratio

Propeller Location	No. Blades	Diameter	Pitch	Developed Area Ratio

Date of last drydocking or bottom cleaning ________

Type of fuel used ________
Fuel sampling location ________
Date and time of fuel sampling ________

Lube oil Type ________
Type and frequency of lube oil treatment ________
Time since last oil treatment or oil change ________
Oil sampling location ________ Oil sampling date and time ________

APPENDIX C

U.S. Coast Guard/U.S. Maritime Administration
Cooperative Research on Marine Engine Exhaust Emissions

EXPERIMENTAL DESIGN FOR

CO-OPERATIVE FUEL RESEARCH (CFR) DIESEL ENGINE EMISSIONS TESTS

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Prepared for:

U.S. DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD
Office of Engineering, Logistics, and Development
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and

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TABLE OF CONTENTS

1.0 Introduction

The U.S. Coast Guard is embarking on a detailed examination of emission factors for C.G. cutters. Laboratory and shipboard tests are being conducted to determine if C.G. cutters meet the standards being promulgated under the Clean Air Act as Amended in 1990 (CAAA90). The laboratory tests conducted using this experimental design will provide guidance for making emission improvements if the standards of CAAA90 are not already met by cutters.

This experimental design will be used for tests on the C.G. Academy's CFR diesel engine. A statistically sound design approach is needed to ensure that the test results are beyond reproach. This is particularly important because the Coast Guard, as the United States representative to the International Maritime Organization (IMO), will present the results for comparison to international test results.

Dependent and independent variables for the experimental design have been previously presented under a separate task for this project. These variables are listed in the sections below.

1.1 Dependent Variables

The dependent variables for this design are the quantities of various gaseous emissions including:

NO
NO_2
SO_2
CO
CO_2
O_2

In the future the same experimental design may be used for studies of hydrocarbons and particulates (after portable techniques for their measurement are established and the equipment is available).

1.2 Independent Variables

The following list shows the independent variables and the respective test levels recommended for tests on the CFR diesel engine. Test levels were chosen after consulting with the Coast Guard CFR engine operators and Waukesha Engine Division of Dresser Industries, the manufacturer of the CFR engine. The maximum torque was chosen under the assumption that the dynamometer on the CFR engine can absorb 5 horsepower continuously. An attempt was made to choose test levels which span as much of the engine operating range as possible without causing engine damage. Since the low and high levels of the independent variables are near the extremes of the operating range, combinations of these extreme values may cause the CFR engine to operate poorly or not at all. Section 6 discusses alternative independent variable levels to use if data can not be obtained at the design data points.

Two fuel types, diesel only and 20/80 diesel/natural gas were originally specified. The discussion on experimental design which follows shows that fewer test runs are needed with 6 variables at 3 levels each than for two tests, one for each fuel type, having 5 variables each. For this reason, the mid-level fuel has been added as a recommended test level.

Test Variable	Low Level	Mid Level	High Level
Engine RPM	600 /min	1200 /min	1800 /min
Engine Torque	1.5 ft-lbs	8.0 ft-lbs	14.5 ft-lbs
Compression Ratio	10:1	20:1	30:1
Inlet Air Restriction (Orifice size)	0.75 inch	1.4 inch	2.049 inch (No orifice)
Injection Timing	16° BTDC	12° BTDC	8° BTDC
Fuel Type	Diesel only	60/40 Diesel/ Natural Gas	20/80 Diesel/ Natural Gas

2.0 Experimental Design Choices

Each of the independent variables is known to affect emissions based on previous engine studies. It is also known that these effects are not linear with the level of individual variables. What has not been studied in detail is the effect of interactions between the independent variables on emissions. Because of the known curvature present, at least 3 levels of the independent variables need to be used. This allows engine emissions to be modelled using a quadratic equation in all possible combinations of variables. With 5 variables, there are 21 second and lower order terms, with 21 unknown coefficients, in the model. For 6 variables, there are 28 second and lower order terms. If third order terms are included, the number of terms increases rapidly. There are 35 third order terms in the 5 variable case. However, three levels of the independent variables do not permit accurate determination of the higher order coefficients. The general modelling equation (6 variables) for the experiment is:

$$\begin{aligned} E_i = {} & a_0 + a_1v_1 + a_2v_2 + a_3v_3 + a_4v_4 + a_5v_5 + a_6v_6 + a_{11}v_1^2 + a_{12}v_1v_2 + a_{13}v_1v_3 + a_{14}v_1v_4 + a_{15}v_1v_5 + a_{16}v_1v_6 \\ & + a_{22}v_2^2 + a_{23}v_2v_3 + a_{24}v_2v_4 + a_{25}v_2v_5 + a_{26}v_2v_6 + a_{33}v_3^2 + a_{34}v_3v_4 + a_{35}v_3v_5 + a_{36}v_3v_6 + a_{44}v_4^2 + a_{45}v_4v_5 \\ & + a_{46}v_4v_6 + a_{55}v_5^2 + a_{56}v_5v_6 + a_{66}v_6^2 + \text{higher order terms} \end{aligned}$$

where E_i are the levels of each dependent variable predicted by the model
v_j are the levels of independent variables
a_k are the unknown coefficients to be found

The minimum number of data points must equal the number of unknown coefficients. However, using the minimum number of data points gives no information about the variability of measurements so additional data must be collected in a practical experiment.

The increase in the number of coefficients for 6 variables vice 5 is not large (33%). Thus, an experiment can be designed with only a few more test runs to determine the output equation. For the emissions experiment, this means that a single experiment including 3 fuel levels would be only a little larger than an experiment with a single fuel. And the single six variable experiment would be significantly smaller than 2 experiments (with 2 different fuels) having 5 independent variables each. This is discussed in more detail below.

2.1 Full Three Level Factorial Design

The most complete design is the three level factorial design which has an experimental run at each combination of levels in the independent variable list above. There are 3^p combinations of variable levels where p is the number of variables in the experiment. For 5 variables there are 243 data points and for 6 variables there are 729. These greatly exceed the minimum numbers of points needed to determine the coefficients in the model equation. Taking this much data would also be excessively time consuming and expensive.

Figure 1 shows a test cube (3 variables) which illustrates the different design choices. Higher level designs can not be easily illustrated but follow the same pattern. All the points illustrated on this cube would be data points in a full three level factorial design.

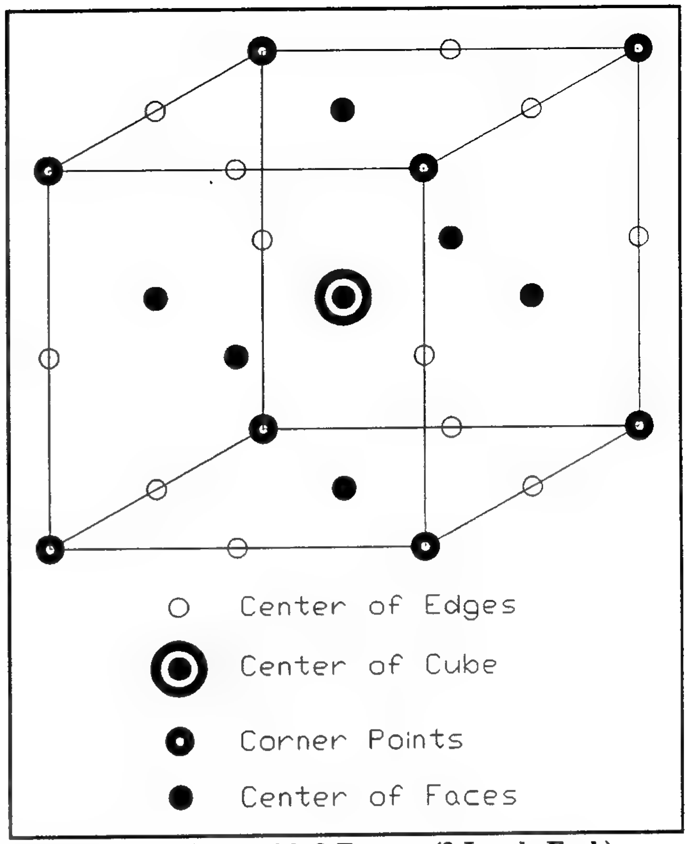

Figure 1 Test Cube with 3 Factors (3 Levels Each)

2.2 Box-Behnken Design

One popular experimental design choice is the Box-Behnken design. In this design, data is only collected at the center point of the cube in Figure 1 and at the center of each edge of the cube. All the center points of the edges are equidistant from the cube center. This has the advantage of determining a value of experimental variance that is nearly constant for all points inside the sphere. This feature also allows all coefficients in the model equation to be predicted with equal precision. The center points of the design hypercube are usually repeated to better determine the variability of measurements. A 5 variable design has 40 edges and a 6 variable design has 48 edges. Thus a 5 variable design with 6 repeats of the center point would consist of 46 test runs while a 6 variable design would require 54 test runs. These numbers of runs should provide good predictions over the model space within the spherical volume without excessive test runs.

However, the volume that lies within the cube but outside the sphere through the data points is outside the model space. Model predictions in this region are extrapolations and may contain significant errors. Unfortunately, the corners of the model space for engine emissions represent frequent operating conditions and we don't want large errors in the prediction model at those points. This limits the usefulness of the Box-Behnken design for the emissions problem.

2.3 Face-Centered Cube Design

Again referring to Figure 1, the face-centered cube design uses data at the corners of the cube, the center of the cube, and at the midpoint of each face (star points). The corner and star points are not equidistant from the cube center. As a result the variance is not the same in all directions from the cube center and the coefficients of some terms in the equation will be predicted with more precision than will others. The variation is proportional to the length of the radius to a face compared to the radius to a corner of the cube. In some experimental designs these problems are overcome by moving the star points out from the face until the radius to the cube center is equal to the distance from the center to a corner. This obtains all the advantages of the Box-Behnken design while

extending the model space to the corners of the cube. Whenever this can be done, it is usually better to expand the model space and use a Box-Behnken design because fewer test runs are required. In the case of engine emissions, the experiment space can not be expanded without damaging the engine. The differences in the radii to the star and corner points can be corrected by applying different weights to the data from these two types of points based on their distance from the center of the hypercube.

Although the experiment space is not uniform around the center, the face-centered cube design offers the distinct advantage of including the corners of the cube in the model space of the prediction equation. A model determined from data in a face-centered cube design is more likely to predict accurately the emissions near the corner regions of the cube than is a model based on a Box-Behnken design. That is the critical point that makes the face-centered cube design the preferred choice for the emissions experiment.

Face-centered cube designs are larger than Box-Behnken designs if all corner points of the hypercube are included. In the case of 5 variables, there are 32 corner points, 10 star points, and 6 center points for a total of 48 runs required. A Box-Behnken design requires 46 data points. With 6 variables there are 64 corner points, 12 star points, and 6 center points for a total of 82 runs compared to 54 Box-Behnken runs. These extra data points help to better predict experimental variance but do little to improve the model equation. A fractional factorial design (2 level) can be used to reduce the number of corner points in the design with little loss of accuracy in the model equation. Fractional factorial designs have to be used with caution if higher order interactions (3 variables or more) are thought to be important because these interaction terms will be confounded with lower order terms. Use of the quadratic model given previously in effect says that we don't think higher order terms are significant.

A half fraction design with 5 variables requires 32 test runs (16 corner points). This is about the minimum practical number of runs to predict 21 coefficients and determine experimental error. With 6 variables, 50 test runs are required. This is still a reasonable number and is comparable to the number of tests in a Box-Behnken design. A full factorial is recommended if 5 variables are included and a half fraction design is recommended with 6 variables. A nice 6 variable fractional design exists that has no confounding of 1st and 2nd order terms with higher order terms. This design is ideal for the emissions tests and its use is discussed in section 4.0.

Note that two 5 variable designs would be needed to obtain data for two fuel types. At a minimum this would require 64 test runs (half fraction) but 116 (full) are recommended for best accuracy. Making the fuel mix a 6th variable and performing a single combined experiment only requires 50 - 82 test runs. Therefore, the 6 variable experiment is highly recommended.

2.4 Randomly Selected Design

Another alternative to the designs in the sections above is to randomly choose somewhere between 50 and 80 data points from the full set of 729 (6 variables). This is chancy. The variance over the model space will not be any better than for the face-centered cube design and the total experimental space may not be covered. There does not appear to be a significant advantage to using a random design over a more structured design provided only second order interactions are of interest.

A possible alternative to the classical face centered cube design can be used if higher order interactions are of interest while maintaining full coverage of the hypercube. This design retains the full or half fractional design corner points but changes the levels of the 6 cube center points and the 12 star points. By varying the levels of the six variables at these design points from approximately 1/4 to 3/4 of the total range, it is possible to determine data at other than the mid level of these variables. Thus, a third or higher order curve can be fitted to the data with higher accuracy. There are insufficient data points to determine all third order interactions but a step-wise regression analysis can be used to determine the most significant 30 - 35 interactions. As a rule, there are fewer significant interactions than 35. A half fractional design using this approach is provided in Section 5.0 but should be used with caution. With a half fractional design, there is confounding of third order effects at the corners so it will not be possible to accurately determine a cause and effect relationship between the third order interactions.

This could be eliminated by use of a full factorial design, but 82 test runs would be required.

3.0 Face-Centered Cube Design with Full Two Level Factorial

The following discussion is based on a 6 variable, face-centered cube design with all the corner points included. Section 4.0 discusses a smaller but similar design which uses only half of the corner points. Either could be used for the diesel engine emission tests but the design in 4.0 is recommended because less data is required. There is also the possibility of running the remaining corner points at a later date if the first test series is conducted using the design of section 4.0. This could be done with the addition of cube center point replications and an additional blocking variable to determine the differences between the two blocks of tests. The data from the two test series could then be combined into the design described in this section.

The runs shown in the following tables have been divided into 2 blocks with all of the star points in the first block. Run order has been randomized except for the center points. The center points have been distributed evenly throughout the series of runs. Table 1 lists the first 50 runs and is identical to the half factorial described in section 4.0. Runs 51 to 87 are shown in Table 2. Five additional runs at the center point have been added in this block on the assumption that the two blocks will be run at different times. If all the data is taken at one time, the five extra center points can be deleted but the remaining 6 center points should be evenly distributed throughout all the runs.

Table 1 Experiment Run Order for 6 Variables (Half Fraction)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)	Fuel Type Nat.Gas/Diesel
1	1.4	8.0	1200	20:1	12°	40/60
2	2.05	14.5	1800	30:1	8°	80/20
3	.75	1.5	1800	30:1	8°	80/20
4	.75	14.5	1800	30:1	8°	0/100
5	.75	14.5	1800	30:1	16°	80/20
6	2.05	14.5	600	10:1	8°	80/20
7	1.4	8.0	1200	20:1	16°	40/60
8	.75	1.5	600	10:1	16°	0/100
9	.75	8.0	1200	20:1	12°	40/60
10	.75	1.5	1800	10:1	16°	80/20
11	1.4	8.0	1200	20:1	12°	40/60
12	.75	1.5	600	30:1	16°	80/20
13	.75	1.5	1800	10:1	8°	0/100
14	.75	14.5	600	30:1	16°	0/100
15	.75	14.5	600	10:1	8°	0/100
16	1.4	8.0	1800	20:1	12°	40/60
17	1.4	8.0	1200	10:1	12°	40/60
18	2.05	1.5	600	30:1	8°	80/20
19	.75	14.5	1800	10:1	8°	80/20
20	.75	1.5	1800	30:1	16°	0/100
21	1.4	8.0	1200	20:1	12°	40/60
22	.75	14.5	1800	10:1	16°	0/100
23	1.4	8.0	1200	30:1	12°	40/60
24	2.05	14.5	1800	30:1	16°	0/100
25	1.4	14.5	1200	20:1	12°	40/60

Table 1 **Experiment Run Order for 6 Variables (Half Fraction) (Continued)**

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)	Fuel Type Nat.Gas/Diesel
26	.75	14.5	600	10:1	16°	80/20
27	2.05	1.5	600	10:1	16°	80/20
28	1.4	8.0	1200	20:1	8°	40/60
29	2.05	14.5	600	30:1	16°	80/20
30	2.05	14.5	1800	10:1	8°	0/100
31	1.4	8.0	1200	20:1	12°	40/60
32	2.05	1.5	600	30:1	16°	0/100
33	1.4	8.0	1200	20:1	12°	80/20
34	2.05	1.5	1800	30:1	16°	80/20
35	.75	1.5	600	10:1	8°	80/20
36	.75	1.5	600	30:1	8°	0/100
37	2.05	8.0	1200	20:1	12°	40/60
38	2.05	14.5	1800	10:1	16°	80/20
39	.75	14.5	600	30:1	8°	80/20
40	2.05	1.5	600	10:1	8°	0/100
41	1.4	8.0	1200	20:1	12°	40/60
42	2.05	1.5	1800	10:1	8°	80/20
43	1.4	1.5	1200	20:1	12°	40/60
44	2.05	1.5	1800	10:1	16°	0/100
45	2.05	1.5	1800	30:1	8°	0/100
46	1.4	8.0	600	20:1	12°	40/60
47	1.4	8.0	1200	20:1	12°	0/100
48	2.05	14.5	600	10:1	16°	0/100
49	2.05	14.5	600	30:1	8°	0/100
50	1.4	8.0	1200	20:1	12°	40/60

Table 2 Experiment Run Order for 6 Variables (Second Half)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)	Fuel Type Nat.Gas/Diesel
51	1.4	8.0	1200	20:1	12°	40/60
52	.75	14.5	600	10:1	8°	80/20
53	2.05	14.5	1800	30:1	8°	0/100
54	.75	1.5	1800	10:1	16°	0/100
55	.75	14.5	1800	30:1	8°	80/20
56	2.05	14.5	600	30:1	8°	80/20
57	.75	14.5	600	10:1	16°	0/100
58	2.05	1.5	600	10:1	8°	80/20
59	2.05	1.5	1800	10:1	16°	80/20
60	1.4	8.0	1200	20:1	12°	40/60
61	2.05	1.5	600	10:1	16°	0/100
62	.75	14.5	600	30:1	8°	0/100
63	.75	14.5	600	30:1	16°	80/20
64	2.05	1.5	600	30:1	16°	80/20
65	2.05	1.5	1800	30:1	8°	80/20
66	.75	1.5	1800	30:1	16°	80/20
67	.75	1.5	600	10:1	8°	0/100
68	2.05	14.5	1800	10:1	16°	0/100
69	1.4	8.0	1200	20:1	12°	40/60
70	2.05	14.5	600	10:1	16°	80/20
71	2.05	14.5	600	30:1	16°	0/100
72	.75	1.5	1800	30:1	8°	0/100
73	.75	1.5	600	30:1	16°	0/100
74	2.05	1.5	1800	30:1	16°	0/100
75	2.05	14.5	600	10:1	8°	0/100

Table 2 **Experiment Run Order for 6 Variables (Second Half) (Continued)**

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)	Fuel Type Nat.Gas/Diesel
76	2.05	1.5	1800	10:1	8°	0/100
77	.75	1.5	600	10:1	16°	80/20
78	1.4	8.0	1200	20:1	12°	40/60
79	2.05	14.5	1800	30:1	16°	80/20
80	.75	14.5	1800	30:1	16°	0/100
81	.75	1.5	600	30:1	8°	80/20
82	.75	14.5	1800	10:1	8°	0/100
83	.75	1.5	1800	10:1	8°	80/20
84	2.05	1.5	600	30:1	8°	0/100
85	.75	14.5	1800	10:1	16°	80/20
86	2.05	14.5	1800	10:1	8°	80/20
87	1.4	8.0	1200	20:1	12°	40/60

Table 3 Alternative Cube Center and Star Points

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)	Fuel Type Nat.Gas/Diesel
1	1.26	6.94	941	17.83:1	13.23°	45/55
7	1.58	4.86	945	16.60:1	16°	49/51
9	.75	6.07	1174	18.29:1	13.87°	47/53
11	1.31	10.47	1270	16.76:1	13.39°	49/51
16	1.08	5.00	1800	22.12:1	12.07°	57/43
17	1.22	5.50	937	10:1	10.54°	54/46
21	1.15	7.25	1171	22.68:1	12.48°	21/79
23	1.52	6.36	1284	30:1	11.14°	38/62
25	1.16	14.5	1324	19.29:1	12.75°	48/52
28	1.18	10.96	1284	18.77:1	8°	54/46
31	1.68	9.89	1213	22.49:1	13.83°	35/65
33	1.63	6.78	992	15.01:1	13.06°	80/20
37	2.05	11.00	1269	16.01:1	12.29°	59/41
41	1.70	10.65	1225	15.34:1	11.04°	57/43
43	1.59	1.5	1467	24.10:1	11.31°	47/53
46	1.19	10.63	600	24.05:1	13.87°	41/59
47	1.66	10.41	1448	22.29:1	11.09°	0/100
50	1.32	6.73	1440	17.21:1	12.88°	23/77

4.0 Face-Centered Cube Design with Half Factorial

The recommended design uses the sequence of independent variable levels shown in Table 1. A minimum of 28 test runs are required to determine the 28 coefficients in the 6 variable equation. The 50 test runs shown in Table 1 provide 22 additional tests to better estimate variance and to provide a balanced estimate over the whole of the operating range. The half fractional design used here collects data at the high and low levels of each variable. Half of the corner points have been selected in such a way that the first and second order terms are not confounded with any higher order terms.

5.0 Alternative Data Points for Center and Star Points

Table 3 provides alternative data points to the cube center and star points for the design in Table 1. The remaining data points in Table 1 are unchanged. The cube center and star points have been replaced with design points at which the values of the six independent variables are randomly selected to fall between 1/4 and 3/4 of the full scale range rather than at the mid level. This alternative design should be used instead of the design in Section

4.0 if third order or higher order interactions are desired. There is confounding of third order effects with this design so it should be used with caution. For this reason, the design in Section 4.0 is recommended.

Note that this design requires that different orifice sizes be used for each of the 18 alternative data points. This will require additional machining work and additional time to change orifices.

6.0 Alternative Independent Variable Levels

Data resulting from this experimental design should be analyzed using a nonlinear stepwise regression analysis or a nonlinear regression such as the Marquardt-Levenberg algorithm. These permit the independent variables to have any level. Therefore, the independent variable levels do not have to be precisely on the design points for a successful result. However, from the point of view of obtaining a balanced regression over the whole operating region, the data should be collected as close to the design points as possible.

There are two main reasons why the independent variables might not land on the design points. The first of these is a lack of ability to set the independent variables exactly on the design points. The second reason is that the engine may not operate properly with the independent variables set on the design points. Both reasons are discussed in the sections that follow.

6.1 Variable Level Settings

The independent variables are all continuous variables. The ease with which these variables can be set to precise values varies. The inlet air restriction is the easiest to set because a set of three orifices are used for all the tests. It is only necessary to machine the orifices to the correct size to set this variable. Compression ratio and injection timing are set with micrometer adjustments on the engine. These adjustments should be very repeatable but the micrometers must be calibrated in advance to determine the corresponding compression ratios and injection timing. Engine RPM will be set and maintained by the dynamometer control system. This should provide high accuracy. The other two variables are not as easy to set.

The recommended method for conducting each test run is to set the desired engine RPM using the dynamometer control system and then add fuel to the engine until it is producing the desired torque. The torque may vary if the engine is not running smoothly. The average torque value readout from the dynamometer will have to be used. It could be difficult to add just enough fuel to obtain the precise average torque level desired so a value reasonably close to the design point may have to be accepted.

For the diesel only runs, the torque is set by a micrometer adjustment to add diesel fuel. This is straight forward and can be set precisely. The micrometer should be calibrated to accurately indicate the fuel consumption. Runs on a natural gas/diesel mixture present a more difficult problem. The natural gas is added to the air stream before it enters the engine based on a differential pressure across an orifice. The diesel fuel is injected into the cylinder. The upstream natural gas pressure is adjustable. A calibration curve must be created in advance which shows the natural gas flow versus differential pressure across the orifice. Both the natural gas flow and the diesel flow have to be adjusted to obtain the desired torque and also the desired natural gas/diesel fuel ratio. This requires a trial and error approach that may end with an approximately correct fuel ratio and engine torque. The engine should be run for a sufficient period before taking data to ensure that the mixture set is the one the engine is operating on. Fuel consumption should be recorded for all runs as well as the actual ratio of natural gas to diesel.

6.2 Changes if Engine Will Not Run Properly

Because the independent variable levels cover most of the range of possible engine operations, it is quite likely that combinations of these extreme values will cause the engine not to run. If this is the case there will be a region of the hypercube surrounding the design point that can not be tested. The tester has the option of approaching the design point along many different paths within the hypercube until the limiting boundary is reached.

The path might be along an edge of the cube or on the radius from the cube center to the design point. Any of these are valid approaches.

From a practical standpoint it is easier to vary the engine torque and RPM than most of the other variables. It is recommended that the following steps be taken if data at a design point can not be obtained.

1. Keep all independent variables at the design levels except engine torque. Reduce (or raise) the torque until the engine can be operated. If the engine torque that results is too close to another data point then go to step 2.

2. Keep all independent variables at the design levels except engine RPM. Reduce (or raise) the RPM until the engine can be operated. If the engine RPM that results is too close to another data point then try step 3.

3. Reduce (or increase) the compression ratio keeping both RPM and torque at the design levels until the engine can be operated or until a point half way to the mid level compression ratio is reached. Then repeat step 1 and, if necessary, 2 with this new compression ratio to get the best performance. If further adjustment is needed, a procedure similar to this step can be tried using injection timing or inlet air restriction as the modified variable.

APPENDIX D

U.S. Coast Guard/U.S. Maritime Administration
Cooperative Research on Marine Engine Exhaust Emissions

EXPERIMENTAL DESIGN FOR

CO-OPERATIVE FUEL RESEARCH (CFR) SPARK IGNITED ENGINE EMISSIONS TESTS

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Prepared for:

U.S. DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD
Office of Engineering, Logistics, and Development
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and

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TABLE OF CONTENTS

1.0 Introduction

The U.S. Coast Guard is embarking on a detailed examination of emission factors for C.G. cutters. Laboratory and shipboard tests are being conducted to determine if C.G. cutters meet the standards being promulgated under the Clean Air Act as Amended in 1990 (CAAA90). The laboratory tests conducted using this experimental design will provide guidance for making emission improvements if the standards of CAAA90 are not already met by cutters.

This experimental design will be used for tests on the C.G. Academy's spark-ignited CFR engine. A statistically sound design approach is needed to ensure that the test results are beyond reproach. This is particularly important because the Coast Guard, as the United States representative to the International Maritime Organization (IMO), will present the results for comparison to international test results.

Dependent and independent variables for the experimental design have been previously presented under a separate task for this project. These variables are listed in the sections below.

1.1 Dependent Variables

The dependent variables for this design are the quantities of various gaseous emissions including:

NO
NO_2
SO_2
CO
CO_2
O_2

In the future the same experimental design may be used for studies of hydrocarbons and particulates (after portable techniques for their measurement are established and the equipment is available).

1.2 Independent Variables

The following list shows the independent variables and the respective test levels recommended for tests on the spark-ignited CFR engine. Test levels were chosen after consulting with the Coast Guard CFR engine operators and Waukesha Engine Division of Dresser Industries, the manufacturer of the CFR engine. The maximum torque was chosen under the assumption that the dynamometer on the CFR engine can absorb 5 horsepower continuously. An attempt was made to choose test levels which span as much of the engine operating range as possible without causing engine damage. Since the low and high levels of the independent variables are near the extremes of the operating range, combinations of these extreme values may cause the CFR engine to operate poorly or not at all. Section 6 discusses alternative independent variable levels to use if data can not be obtained at the design data points.

Tests are required using two fuel types, gasoline and propane. The engine configuration for these two fuels is very different which makes a combined test with gasoline and propane impractical. Therefore, two separate five variable experiments must be conducted, one with each fuel.

Test Variable	Low Level	Mid Level	High Level
Engine RPM	600 /min	1200 /min	1800 /min
Engine Torque	1.5 ft-lbs	8.0 ft-lbs	14.5 ft-lbs
Compression Ratio	5:1	10:1	15:1
Inlet Air Restriction (Orifice size)	0.75 inch	1.4 inch	2.049 inch (No orifice)
Injection Timing	25° BTDC	15° BTDC	5° BTDC

2.0 Experimental Design Choices

Each of the independent variables is known to affect emissions based on previous engine studies. It is also known that these effects are not linear with the level of individual variables. What has not been studied in detail is the effect of interactions between the independent variables on emissions. Because of the known curvature present, at least 3 levels of the independent variables need to be used. This allows engine emissions to be modelled using a quadratic equation in all possible combinations of variables. With 5 variables, there are 21 second and lower order terms, with 21 unknown coefficients, in the model. If third order terms are included, the number of terms increases rapidly. There are 35 third order terms in the 5 variable case. However, three levels of the independent variables do not permit accurate determination of the higher order coefficients. The general modelling equation (5 variables) for the experiment is:

$$E_i = a_0 + a_1v_1 + a_2v_2 + a_3v_3 + a_4v_4 + a_5v_5 + a_{11}v_1^2 + a_{12}v_1v_2 + a_{13}v_1v_3 + a_{14}v_1v_4 + a_{15}v_1v_5 + a_{22}v_2^2 + a_{23}v_2v_3 + a_{24}v_2v_4 + a_{25}v_2v_5 + a_{33}v_3^2 + a_{34}v_3v_4 + a_{35}v_3v_5 + a_{44}v_4^2 + a_{45}v_4v_5 + a_{55}v_5^2 + \text{higher order terms}$$

where E_i are the levels of each dependent variable predicted by the model

v_j are the levels of independent variables

a_k are the unknown coefficients to be found

The minimum number of data points must equal the number of unknown coefficients. However, using the minimum number of data points gives no information about the variability of measurements so additional data must be collected in a practical experiment.

2.1 Full Three Level Factorial Design

The most complete design is the three level factorial design which has an experimental run at each combination of levels in the independent variable list above. There are 3^p

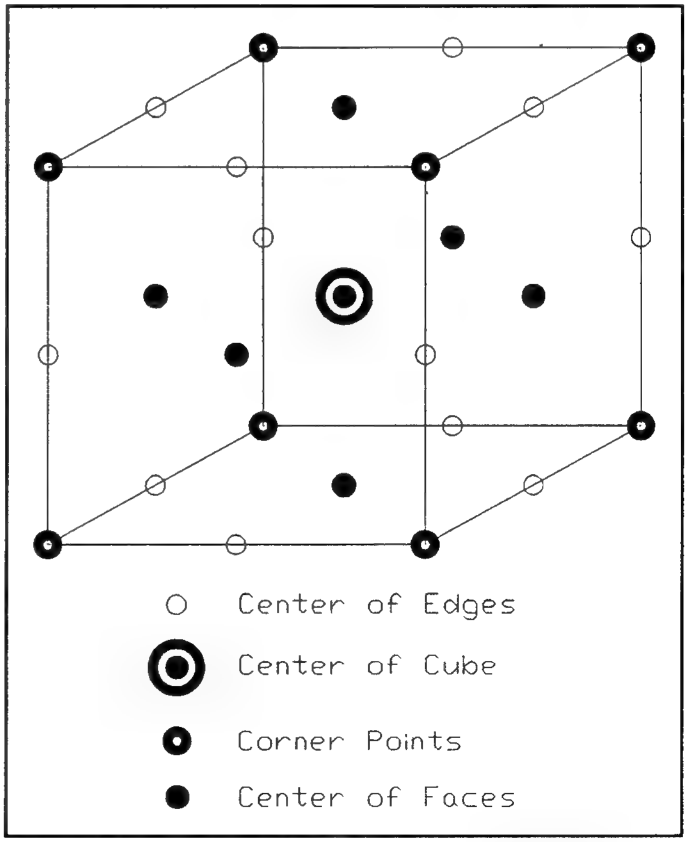

Figure 1 Test Cube with 3 Factors (3 Levels Each)

combinations of variable levels where p is the number of variables in the experiment. For 5 variables there are 243 data points. These greatly exceed the minimum numbers of points needed to determine the coefficients in the model equation. Taking this much data would also be excessively time consuming and expensive.

Figure 1 shows a test cube (3 variables) which illustrates the different design choices. Higher level designs can not be easily illustrated but follow the same pattern. All the points illustrated on this cube would be data points in a full three level factorial design.

2.2 Box-Behnken Design

One popular experimental design choice is the Box-Behnken design. In this design, data is only collected at the center point of the cube in Figure 1 and at the center of each edge of the cube. All the center points of the edges are equidistant from the cube center. This has the advantage of determining a value of experimental variance that is nearly constant for all points inside the sphere. This feature also allows all coefficients in the model equation to be predicted with equal precision. The center points of the design hypercube are usually repeated to better determine the variability of measurements. A 5 variable design has 40 edges. Thus a 5 variable design with 6 repeats of the center point would consist of 46 test runs. This number of runs should provide good predictions over the model space within the spherical volume without excessive test runs.

However, the volume that lies within the cube but outside the sphere through the data points is outside the model space. Model predictions in this region are extrapolations and may contain significant errors. Unfortunately, the corners of the model space for engine emissions represent frequent operating conditions and we don't want large errors in the prediction model at those points. This limits the usefulness of the Box-Behnken design for the emissions problem.

2.3 Face-Centered Cube Design

Again referring to Figure 1, the face-centered cube design uses data at the corners of the cube, the center of the cube, and at the midpoint of each face (star points). The corner and star points are not equidistant from the cube center. As a result the variance is not the same in all directions from the cube center and the coefficients of some terms in the equation will be predicted with more precision than will others. The variation is proportional to the length of the radius to a face compared to the radius to a corner of the cube. In some experimental designs these problems are overcome by moving the star points out from the face until the distance to the cube center is equal to the distance from the center to a corner. This obtains all the advantages of the Box-Behnken design while extending the model space to the corners of the cube. Whenever this can be done, it is usually better to expand the model space and use a Box-Behnken design because fewer test runs are required. In the case of engine emissions, the experiment space can not be expanded without damaging the engine. The differences in the radii to the star and corner points can be corrected by applying different weights to the data from these two types of points based on their distance from the center of the hypercube.

Although the experiment space is not uniform around the center, the face-centered cube design offers the distinct advantage of including the corners of the cube in the model space of the prediction equation. A model determined from data in a face-centered cube design is more likely to predict accurately the emissions near the corner regions of the cube than is a model based on a Box-Behnken design. That is the critical point that makes the face-centered cube design the preferred choice for the emissions experiment.

Face-centered cube designs are slightly larger than Box-Behnken designs if all corner points of the hypercube are included. In the case of 5 variables, there are 32 corner points, 10 star points, and 6 center points for a total of 48 runs required. A Box-Behnken design requires 46 data points. The extra data points help to better predict experimental variance but do little to improve the model equation. A fractional factorial design (2 level) can be used to reduce the number of corner points in the design with little loss of accuracy in the model equation. Fractional factorial designs have to be used with caution if higher order interactions (3 variables or more) are

thought to be important because these interaction terms will be confounded with lower order terms. Use of the quadratic model given previously in effect says that we don't think higher order terms are significant.

A half fraction design with 5 variables requires 32 test runs (16 corner points). This is about the minimum practical number of runs to predict 21 coefficients and determine experimental error. A full factorial is recommended for the 5 variable design.

Note that two 5 variable designs are needed to obtain data for two fuel types. At a minimum this would require 64 test runs (half fraction) but 96 runs (full) are recommended for best accuracy.

2.4 Randomly Selected Design

Another alternative to the designs in the sections above is to randomly choose somewhere between 40 and 60 data points from the full set of 243. This is chancy. The variance over the model space will not be any better than for the face-centered cube design and the total experimental space may not be covered. There does not appear to be a significant advantage to using a random design over a more structured design provided only second order interactions are of interest.

A possible alternative to the classical face centered cube design can be used if higher order interactions are of interest while maintaining full coverage of the hypercube. This design retains the full factorial design corner points but changes the levels of the 6 cube center points and the 10 star points. By varying the levels of the five variables at these design points from approximately 1/4 to 3/4 of the total range, it is possible to determine data at other than the mid level of these variables. Thus, a third or higher order curve can be fitted to the data with higher accuracy. There are insufficient data points to determine all third order interactions but a step-wise regression analysis can be used to determine the most significant 30 - 35 interactions. As a rule, there are fewer significant interactions than 35. A full factorial design using this approach is provided in Section 5.0.

3.0 Face-Centered Cube Design with Full Two Level Factorial

The following discussion is based on a 5 variable, face-centered cube design with all the corner points included. Section 4.0 discusses a smaller but similar design which uses only half of the corner points. Either could be used for the spark-ignited engine emission tests but the design in this section is recommended because there is no confounding of the data with higher order terms and the number of runs for a full factorial designs is not excessive.

Table 1 gives the design points for the full factorial design. Run order has been randomized except for the center points. The center points have been distributed evenly throughout the series of runs.

4.0 Face-Centered Cube Design with Half Factorial

The half fractional factorial design uses the sequence of independent variable levels shown in Table 2. A minimum of 21 test runs are required to determine the 21 coefficients in the 5 variable equation. The 32 test runs shown in Table 2 provide 11 additional tests to better estimate variance and to provide a balanced estimate over the whole of the operating range. The half fractional design used here collects data at the high and low levels of each variable. The first and second order terms are all confounded with higher order terms as shown below:

1 = 2345	12 = 345	23 = 145	34 = 125
2 = 1345	13 = 245	24 = 135	35 = 124
3 = 1245	14 = 235	25 = 134	
4 = 1235	15 = 234		45 = 123
5 = 1234			

As an example, it is not possible with the half fractional design to separate the contribution of variable v_1 alone from the combined contribution of $v_2v_3v_4v_5$. The contribution of $v_2v_3v_4v_5$ to the result is usually much smaller than the contribution of v_1 and can often be ignored.

5.0 Alternative Data Points for Center and Star Points

Table 3 provides alternative data points to the cube center and star points for the design in Table 1. The remaining data points in Table 1 are unchanged. The cube center and star points have been replaced with design points at which the values of the five independent variables are randomly selected to fall between 1/4 and 3/4 of the full scale range rather than at the mid level. This alternative design should be used instead of the design in Section 4.0 if third order or higher order interactions are desired.

Note that this design requires that different orifice sizes be used for each of the 16 alternative data points. This will require additional machining work and additional time to change orifices.

6.0 Alternative Independent Variable Levels

Data resulting from this experimental design should be analyzed using a nonlinear stepwise regression analysis or a nonlinear regression such as the Marquardt-Levenberg algorithm. These permit the independent variables to have any level. Therefore, the independent variable levels do not have to be precisely on the design points for a successful result. However, from the point of view of obtaining a balanced regression over the whole operating region, the data should be collected as close to the design points as possible.

There are two main reasons why the independent variables might not land on the design points. The first of these is a lack of ability to set the independent variables exactly on the design points. The second reason is that the engine may not operate properly with the independent variables set on the design points. Both reasons are discussed in the sections that follow.

6.1 Variable Level Settings

The independent variables are all continuous variables. The ease with which these variables can be set to precise values varies. The inlet air restriction is the easiest to set because a set of three orifices are used for all the tests. It is only necessary to machine the orifices to the correct size to set this variable. Compression ratio and spark timing are set with adjustments on the engine. These adjustments should be very repeatable but the adjustments must be calibrated in advance to determine the corresponding compression ratios and spark timing. Engine RPM will be set and maintained by the dynamometer control system. This should provide high accuracy. The other two variables are not as easy to set.

The recommended method for conducting each test run is to set the desired engine RPM using the dynamometer control system and then add fuel to the engine until it is producing the desired torque. The torque may vary if the engine is not running smoothly. The average torque value readout from the dynamometer will have to be used. It could be difficult to add just enough fuel to obtain the precise average torque level desired so a value reasonably close to the design point may have to be accepted.

Whether gasoline or propane is used, only a single fuel adjustment is needed. Fuel adjustment is straight forward and can be set precisely. The micrometer should be calibrated to accurately indicate the fuel consumption.

Table 1 Experiment Run Order for 5 Variables (Full Factorial)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Spark Timing (BTDC)
1	1.4	8.0	1200	10:1	15°
2	2.05	1.5	1800	5:1	5°
3	1.4	8.0	600	10:1	15°
4	2.05	14.5	600	15:1	5°
5	1.4	1.5	1200	10:1	15°
6	.75	1.5	600	5:1	25°
7	2.05	1.5	1800	15:1	5°
8	2.05	14.5	600	15:1	25°
9	1.4	8.0	1200	10:1	15°
10	.75	1.5	1800	15:1	5°
11	.75	1.5	1800	5:1	5°
12	2.05	14.5	600	5:1	25°
13	1.4	14.5	1200	10:1	15°
14	1.4	8.0	1200	5:1	15°
15	.75	14.5	1800	5:1	25°
16	2.05	8.0	1200	10:1	15°
17	.75	14.5	600	15:1	25°
18	2.05	14.5	600	5:1	5°
19	1.4	8.0	1200	10:1	15°
20	.75	14.5	600	15:1	5°
21	.75	1.5	1800	15:1	25°
22	2.05	14.5	1800	5:1	5°
23	2.05	1.5	600	15:1	25°
24	.75	1.5	600	5:1	5°
25	.75	14.5	600	5:1	5°

Table 1 Experiment Run Order for 5 Variables (Full Factorial) (Continued)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Spark Timing (BTDC)
26	1.4	8.0	1200	15:1	15°
27	.75	8.0	1200	10:1	15°
28	2.05	1.5	600	5:1	25°
29	1.4	8.0	1200	10:1	15°
30	.75	1.5	600	15:1	5°
31	.75	14.5	1800	5:1	5°
32	2.05	14.5	1800	15:1	5°
33	2.05	14.5	1800	5:1	25°
34	.75	1.5	1800	5:1	25°
35	.75	1.5	600	15:1	25°
36	1.4	8.0	1800	10:1	15°
37	2.05	1.5	1800	15:1	25°
38	1.4	8.0	1200	10:1	5°
39	1.4	8.0	1200	10:1	15°
40	.75	14.5	1800	15:1	25°
41	2.05	1.5	1800	5:1	25°
42	1.4	8.0	1200	10:1	25°
43	2.05	1.5	600	15:1	5°
44	2.05	14.5	1800	15:1	25°
45	2.05	1.5	600	5:1	5°
46	.75	14.5	600	5:1	25°
47	.75	14.5	1800	15:1	5°
48	1.4	8.0	1200	10:1	15°

Table 2 Experiment Run Order for 5 Variables (Half Fraction)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Spark Timing (BTDC)
1	1.4	8.0	1200	10:1	15°
2	.75	1.5	600	5:1	5°
3	.75	14.5	1800	15:1	25°
4	.75	14.5	600	5:1	25°
5	2.05	14.5	1800	5:1	25°
6	2.05	1.5	600	15:1	5°
7	1.4	8.0	1200	10:1	15°
8	2.05	8.0	1200	10:1	15°
9	2.05	1.5	1800	15:1	25°
10	.75	14.5	600	15:1	5°
11	2.05	14.5	600	5:1	5°
12	.75	1.5	1800	15:1	5°
13	1.4	8.0	1200	10:1	15°
14	.75	8.0	1200	10:1	15°
15	.75	1.5	600	5:1	5°
16	1.4	8.0	1200	10:1	25°
17	1.4	8.0	1200	5:1	15°
18	1.4	14.5	1200	10:1	15°
19	1.4	8.0	1200	10:1	15°
20	2.05	14.5	600	15:1	25°
21	.75	1.5	1800	5:1	25°
22	2.05	14.5	1800	15:1	5°
23	.75	14.5	1800	5:1	5°
24	1.4	1.5	1200	10:1	15°
25	1.4	8.0	1200	10:1	15°

Table 2 Experiment Run Order for 5 Variables (Half Fraction) (Continued)

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Injection Timing (BTDC)
26	1.4	8.0	1200	10:1	5°
27	2.05	1.5	600	5:1	25°
28	1.4	8.0	1200	15:1	15°
29	2.05	1.5	1800	5:1	5°
30	1.4	8.0	1800	10:1	15°
31	1.4	8.0	600	10:1	15°
32	1.4	8.0	1200	10:1	15°

Table 3 Alternative Cube Center and Star Points

Run No.	Inlet Air Orifice Size (Inches)	Engine Torque (Ft-lbs)	Engine RPM (rev/min)	Compression Ratio	Spark Timing (BTDC)
1	1.45	7.13	1155	9.20:1	17.07°
3	1.51	8.20	600	9.14:1	15.61°
5	1.39	1.5	1278	7.96:1	19.10°
9	1.19	11.19	955	10.97:1	12.32°
13	1.62	14.5	923	8.87:1	15.13°
14	1.37	6.30	1387	5:1	14.84°
16	2.05	5.57	1397	9.76:1	13.43°
19	1.55	8.97	1033	10.49:1	17.80°
26	1.64	5.67	1064	15:1	14.72°
27	.75	8.21	1188	8.41:1	18.56°
29	1.69	6.60	1111	12.31:1	12.61°
36	1.25	10.45	1800	10.90:1	15.24°
38	1.21	11.23	1435	10.23:1	5°
39	1.65	6.77	1141	69.10:1	13.70°
42	1.19	6.95	1472	9.15:1	25°
48	1.64	7.11	1366	11.54:1	15.56°

The engine should be run for a sufficient period before taking data to ensure that the mixture set is the one the engine is operating on. Fuel consumption should be recorded for all runs as well as the actual ratio of natural gas to diesel.

6.2 Changes if Engine Will Not Run Properly

Because the independent variable levels cover most of the range of possible engine operations, it is quite likely that combinations of these extreme values will cause the engine not to run. If this is the case there will be a region of the hypercube surrounding the design point that can not be tested. The tester has the option of approaching the design point along many different paths within the hypercube until the limiting boundary is reached. The path might be along an edge of the cube or on the radius from the cube center to the design point. Any of these are valid approaches.

From a practical standpoint it is easier to vary the engine torque and RPM than most of the other variables. It is recommended that the following steps be taken if data at a design point can not be obtained.

1. Keep all independent variables at the design levels except engine torque. Reduce (or raise) the torque until the engine can be operated. If the engine torque that results is too close to another data point then go to step 2.

2. Keep all independent variables at the design levels except engine RPM. Reduce (or raise) the RPM until the engine can be operated. If the engine RPM that results is too close to another data point then try step 3.

3. Reduce (or increase) the compression ratio keeping both RPM and torque at the design levels until the engine can be operated or until a point half way to the mid level compression ratio is reached. Then repeat step 1 and, if necessary, 2 with this new compression ratio to get the best performance. If further adjustment is needed, a procedure similar to this step can be tried using spark timing or inlet air restriction as the modified variable.